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EMPIRICAL PROBABILITIES ON THE ICE LIMIT AND FIFTY PERCENT ICE --ETC(U)
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EMPIRICAL PROBABILITIES OF THE ICE LIMIT AND FIFTY PERCENT ICE CONCENTRATION BOUNDARY IN THE CHUKCHI AND BEAUFORT SEAS

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UNITED STATES DEPARTMENT OF COMMERCE / Malcolm Baldrige, Secretary
National Oceanic and Atmospheric Administration / John V Byrne, Administrator
National Weather Service / Richard E Hallgren, Director

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ABSTRACT. Semi-monthly empirical probabilities of the ice limit and 50 percent ice concentration boundary are contoured in 25 percent increments from 0 to 100 percent for the Chukchi and Beaufort Seas from May 15 to December 1. The source information covers a 29 year period, from 1953 to 1981.

Given certain assumptions, this statistical approach provides a basis for prediction of the ice extent in the long term which may be some benefit in the seasonal planning of marine operations.

The ice decay and growth cycle shows a distinctive climatological pattern which is related to bottom topography, proximity to warm water sources and a semi-permanent ice circulation feature.

1. INTRODUCTION

This publication presents a climatology of the sea ice extent in the Chukchi and Beaufort Seas in terms of empirical probabilities of the ice limit and 50 percent ice concentration boundary in semi-monthly intervals from May 15 to December 1, based on ice data covering a 29 year period (1953-1981). The purpose of this study is two-fold: First, to update an earlier climatological analysis (Potocsky, 1975) with sea ice data available from 1971-1981 and second, to present the climatology in a format which can be used as a basis for sea ice prediction in the long term.

The empirical probabilities are given in 25 percent increments from 0 to 100 percent with the 0, 50, and 100 percent probability isopleths depicting, respectively, the extreme southerly, the median, and extreme northerly position of the ice limit and 50 percent ice concentration boundary. The latter boundary was chosen for study because Barnett (1976) arbitrarily uses the 50 percent ice edge as one of the indices of North Slope ice conditions for the reason that conventional vessels may negotiate (with caution) sea ice of less than 50 percent concentration while higher concentrations jeopardize safe passage (without ice breaker support). Probabilities of the 50 percent ice concentration boundary are not explicitly included for November 1 and 15 and December 1 since observation shows the ice limit and 50 percent ice concentration boundary to be nearly coincident during the winter freezeup period.

The methodology and results of this study are discussed at length in the following sections of this report.

2. DATA AND METHOD

Ice information for this study was obtained from the following sources: (1) annual reports detailing the U.S. Navy's Arctic ice observing and forecasting program (1953-1971), (2) the U.S. Navy's Western Arctic sea ice analyses (1972-1981), (3) narrative sea ice advisories for western and Arctic Alaskan coastal waters prepared by the National Weather Service (1976-1981), (4) monthly and semi-monthly (June-October 1977-1981) contractual reports prepared by the Arctic Institute of North America and Sea Ice Consultants, Inc., (5) annual ice summaries and ice analyses for the Canadian Arctic by Ice Forecasting Central (1965, 1966, 1968, 1970) and (6) miscellaneous sources not constituent of the above including aircraft reconnaissance, ship reports, etc.

From the source information covering a 29 year period, determination of the ice limit and the boundary of 50 percent ice concentration was attempted for the first and fifteenth of each month from May 15 to December 1. The data were largely typified by maps of ice conditions interpreted from airborne and, since 1968, satellite observations. Since the observations were taken at irregular intervals, it was often necessary to employ estimative techiques to determine the ice boundaries on the semi-monthly dates. These techniques consisted of linearly interpolating between ice observations; extrapolating ice conditions based on continuity augmented by the average expansion and recession rates of the median ice edge calculated by Potocsky (1975); and subjectively determining ice conditions from fragmented observations using climatology. When more than one interpretation of ice conditions for the same area were on hand, an average was usually taken with the exception that aircraft observation was preferred (because of detail) to that of satellite. The next step was to tabulate the latitude of the semi-monthly ice limits and 50 percent ice concentration boundaries for every 2.5 degrees of longitude between 125°W and 170°E. With reference to Panofsky and Brier (1958), the statistical method entailed calculating the cumulative frequency distribution of the latitudes for each longitude expressed in percent from zero to 100. The latitude corresponding to the zero percent frequency is "imaginary" and derived by subtracting one-tenth of a degree from the lowest latitude in the distribution, whereas the latitude corresponding to 100 percent frequency is the latitude at the top of the distribution. Besides the zero and 100 percent frequency, the 25, 50 (median), and 75 percent frequencies were chosen with equivalent latitudes calculated by linear interpolation when needed. Since, by definition, percentage frequency is synonymous with empirical probabilities, contouring the five frequency isopleths yielded the desired ice edge empirical probability charts (figures 2-26). The number of latitudes composing the distribution for each longitude appears at the top of the figures.

CONTENTS

FIGURES

3. DISCUSSION

Figures 2 through 26 give the probabilities of the ice limit (edge of all ice) and 50 percent concentration boundary (close pack ice or greater) at semi-monthly intervals from May 15 to October 15. Only the probabilities of the ice limit are given for November 1 and 15, and December 1, since the ice limit also approximates the 50 percent ice concentration boundary during the height of freezeup. Of the five probabilities, the 0, 50, and 100 percent isopleths are the most significant, depicting, respectively, the extreme maximum, median and extreme minimum ice extent.

Presenting the climatology of ice conditions in the Chukchi and Beaufort Seas in terms of empirical probabilities allows this analysis to be used as a basis for predicting the ice extent in the long range. But, for this to be acceptable, it must be assumed that there are sufficient observations to make the probabilities reliable and that future empirical probabilities will not differ markedly from past empirical probabilities (Panofsky and Brier, 1958).

With prediction in mind then, the 50 percent probability isopleth delineating the median ice edge can be regarded as the demarcation between "likely" (50 percent probability or greater) and "unlikely" (less than 50 percent probability) that sea ice will be present. If, for example, one is concerned about a marine transit to Barter Island from the west around the first of August, then, looking at figure 12, it is seen that sea ice will likely be encountered at about Wainwright and more likely to be found against the Arctic coast east of Barrow. However, figure 13 reveals that there is less than a 50 percent chance that this ice will be close packed (50 percent ice concentration) and obstruct the transit route within a few miles of shore in all locations <u>except</u> right at Point Barrow which is traditionally regarded as a "choke point" at this time of year.

The following section generalizes ice conditions over the Chukchi and Beaufort Seas as interpreted from the series of ice edge probability charts.

<u>Chukchi Sea</u>

The Chukchi Sea is a southern extension of the Arctic Ocean with its southern limit at the Bering Straits and its northern limit marked by a line from Point Barrow to the northern extremity of Wrangell Island (USCG Pilot-9).

The Chukchi Sea remains virtually ice covered from the beginning of December into mid-May with the exception that a relatively wide shore lead may develop seaward of the shorefast ice along the northwest coast, particularly from near Point Lay to Point Barrow during periods of strong easterly winds.

Thicknesses of the annual ice typically range from 100 to 120 cm with thicknesses of multi-year ice encroaching into the northern extremities of the Chukchi Sea approaching 3 meters. Because of the southward-converging Alaskan and Siberian coastlines and the pressure exerted on the ice cover by the expanding polar ice pack, Chukchi Sea ice is heavily deformed. Pressure ridges may be two to three meters high but are frequently much higher in the near-coastal shear zones where drift ice grinds against the stable shorefast ice.

Around mid-May, the seasonal disintegration of the ice cover begins as shorefast ice and thin ice decay and loosen along the northwest Alaskan coast and in the interior of Kotzebue Sound as suggested by the slight reduction in probabilities of the close pack ice boundary in figure 3.

It is not until the beginning of July that a significant reduction in probabilities of both the ice limit and 50 percent ice concentration boundary occurs in the southern Chukchi Sea. The northward arcing of the probability contours in figures 8 and 9 clearly shows the disintegrative influence on the ice cover of the tongue of warm water flowing northward through the Bering Straits. The probability of close pack ice falls to less than 50 percent south of Cape Lisburne and in a narrow corridor along the coast northeastward to Wainwright. This early lead formation is likely a result of a northeastward setting stream of warm water branching from a general northward flow of water in the vicinity of Cape Lisburne referred to by Paquette and Bourke (1974) as the Alaskan Coastal Stream. However, the presence of decaying ice fields still adhering to the shore along the Alaskan northwest coast may complicate marine operations involving shore facilities.

By the beginning of August, a narrow shore lead is likely to develop along the coast between Wainwright and Barrow village as the probabilities of encountering close pack ice fall to about 25 percent. However, as figure 13 reveals, there still remains a good chance that "heavy" ice concentrations will prevail in the area of Point Barrow and over the Chukchi Sea generally as far south as 71°N latitude.

A permanent circulation feature in the Arctic basin, which shunts ice westward north of the Alaskan mainland and then northwestward between 155°W and 160°W longitude, maintains relatively high ice probabilities north of the mainland between Wainwright and Point Barrow throughout August and into September (figures 12 through 17). The withdrawal of the ice pack is seen to be greatest over the Chukchi Sea between 162°W and 175°W during this period, and least north of eastern Siberia. The persistence of sea ice west of 175°W seems largely due to the lack of any warm water inflow into the region to accelerate melting.

The seasonal withdrawal of the ice pack from the Chukchi Sea, exhibits, mainly in August, certain climatological configurations which have been related to current steering by bottom topography (Paquette and Bourke, 1974). These features are evident from the wave-like arrangement of the probability contours for both the ice limit and 50 percent ice concentration boundary for August. Figures 12-15 reveal a southward protrusion of high ice probabilities along 170°W longitude and, to a lesser extent, just to the west of 160°W longitude while lower ice probabilities project northward, generally along 172.5°W and 168°W. The literature associates these northward projections of lower ice probabilities with troughs in the sea floor which concentrate and direct the current into the marginal ice zone, thus creating bays of lower ice concentrations or open water. These features become less definable in figures 16-19 as the melt season progresses into September and the ice recedes farther northward over the continental shelf.

The northward retreat of the ice pack peaks in mid-September when the median ice limit moves north of the Chukchi Sea to about 72°N latitude (figure 18) and the median edge of close pack ice recedes to near 73°N (figure 19). Both of these figures also show that the variability of the ice extent measured by the range of its extremes is highest in mid-September in comparison to the rest of the melt season. For instance, six degrees of latitude separates the extremes of the ice limit at 167°W with a similar difference observed in the extremes of the 50 percent ice concentration boundary at 162°W.

The perennial polar pack in the Arctic Ocean begins its southward advance in late September evidenced by the increasing ice edge probabilities north of the Chukchi Sea on the October 1 charts (figures 20 and 21). By mid-October, (figures 22 and 23) it is likely that sea ice will be found in the proximity of Barrow, but will likely be less than 50 percent concentrated consisting mainly of new ice developing in situ. In extremely cold weather, new ice can develop in the coastal area as far south as Kotzebue Sound.

After mid-October, sea ice forms more rapidly next to the cooling Alaskan land mass than over the Chukchi Sea waters farther removed from the source of cold air. Figure 24 shows that by November, sea ice will likely be extensive in the coastal waters from Cape Lisburne northward as well as in the interior of Kotzebue Sound. Farther westward the probabilities of the ice limit and 50 percent ice concentration boundary are lower with the contour pattern similar to that occurring during the ice melt-back period in August and September, presumably due to bathymetrically-induced current steering previously discussed. Freezeup is rapid during the first half of November and by the fifteenth it is likely that the waters north of the Bering Straits will be ice covered (figure 25) becoming absolutely ice covered by December 1 (figure 26).

Beaufort Sea

The northern limit of the Beaufort Sea is marked by a line from Point Barrow, Alaska, to Lands End on St. Patrick's Island in the Canadian Archipelago (USCG Pilot-9). Due to its proximity to the perennial Arctic Ocean pack ice, the Beaufort Sea is never absolutely ice-free. Pack ice is pushed toward the Alaskan mainland by a clockwise circulating current called the Beaufort Gyre (Sater et al., 1971) which lies between Alaska, the Canadian Archipelago, and the North Pole. Typical ice thicknesses range from 120 to 180 cm in the southern Beaufort Sea (annual or first year ice) to over 3 meters in the Arctic Ocean (multi-year ice).

The initial signs of the melt season in the Beaufort Sea occur in late May with the disappearance of the snow cover from the coastal fast ice and the subsequent thawing and puddling of the shorefast ice in June (Barry et al., 1976). Breakup is more rapid in the southeastern Beaufort Sea than elsewhere in the Beaufort Sea (or the Chukchi Sea) due, in large part, to the warm water outflow from the MacKenzie River. Figure 5 shows the median edge of the 50 percent ice boundary to lie off the coast between Cape Parry and the MacKenzie Delta by June 1, suggesting that the previously consolidated land-fast ice has broken and melted into lower concentrations of drifting ice.

Although the charts indicate no appreciable reduction in ice probabilities along the Alaskan mainland between Point Barrow and Barter Island until the beginning of August, open water areas can develop within the land-fast ice zone mainly in the near coastal area as early as the beginning of June (Stringer et al., 1980). By late July, disintegration of the land-fast ice into light concentrations of drifting pack ice is complete. Figure 13 reveals that, except for the Point Barrow area, there is a less than 50 percent chance of contacting close pack ice in a narrow corridor along the Alaskan Arctic coast and generally over the continental shelf region in the Canadian sector on August 1.

During the first half of August, high probabilities of close pack ice remain ominously close to the operating corridor along the Alaskan coast. Traditionally, this is the period that the marine ferrying of cargo to various establishments along the Alaskan coast commences. By August 15, as figure 15 shows, the median edge of the 50 percent ice boundary lies far enough north of the coast to support the seasonal planning of such operations based on climatology which, though, in this case has already been determined by experience.

Marine operations become less jeopardized by the incursion of close pack ice into the transit route as the melt-back of the Beaufort Sea ice continues into mid-September. Though the southern Beaufort Sea never becomes absolutely ice-free like the southern Chukchi Sea, the chance of encountering close pack ice drops to near 25 percent along the Alaskan north coast and to zero percent along the Canadian coast from MacKenzie Bay eastward by September 1 (figure 17). Further reduction of the probabilities occurs through mid-September at which time they are lowest for the season (indicating the seasonal maximum retreat of the ice pack). Referring to figures 18 and 19, it is seen that for the first time in these semi-monthly intervals that the median edge of the ice limit has receded from off the Alaskan coast and that the median edge of the 50 percent ice concentration boundary has cleared the continental shelf across the entire southern Beaufort Sea.

During the latter half of September, freezeup begins in the Beaufort Sea ice pack followed by new ice development along the mainland in late September or early October. The position of the median edge of the ice limit in figure 20 suggests that new ice formation is more likely along the Alaskan coast between Point Barrow and Prudhoe Bay at the beginning of October than along the remainder of the Beaufort Sea coast which lies at lower latitudes. However, the increase in ice limit probabilities along the mainland, which implies new ice formation, will not likely hinder marine operations at the beginning of October since the median edge of close pack ice still lies well offshore (figure 21).

As freezeup proceeds, new ice spreads northward from the Beaufort Sea coast eventually mixing with the offshore pack ice expanding southward over the continental shelf. By mid-October, it is likely that the overall ice concentration will exceed 50 percent in the southern Beaufort Sea (figure 23), although some open water may persist between the coastal ice zone and the expanding polar pack well into October, especially if the polar pack is at high latitudes at the time of freezeup.

As figure 24 shows, freezeup of the Beaufort Sea is categorical by November as evidenced by the displacement of the 100 percent probability line to the Arctic coast.

4. SUMMARY

This report shows the seasonal pattern of the summer decay and winter growth of the sea ice cover in the Chukchi and Beaufort Seas in terms of empirical probabilities of the ice limit and 50 percent ice concentration boundary from May 15 to December 1. Given certain assumptions, this statistical analysis provides a basis for predicting the extent of sea ice in the long term, thus facilitating the seasonal planning of arctic marine operations. Comparison of the probabilities of the ice limit and 50 percent concentration boundary allows the user to discriminate between navigable ice conditions and ice conditions generally precluding conventional navigation.

The summer retreat of the ice pack is seen to be largest over the Chukchi Sea and southeastern Beaufort Sea where the continental shelf is most expansive and where the ice cover is subjected to warm water influences. In contrast, the ice pack maintains a relatively close summertime posture to Alaska's north coast where the continental shelf is narrowest, warm water sources are comparatively slight, and the ice drift is climatologically shoreward.

ACKNOWLEDGEMENTS

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FIGURE 1 LOCATION MAP

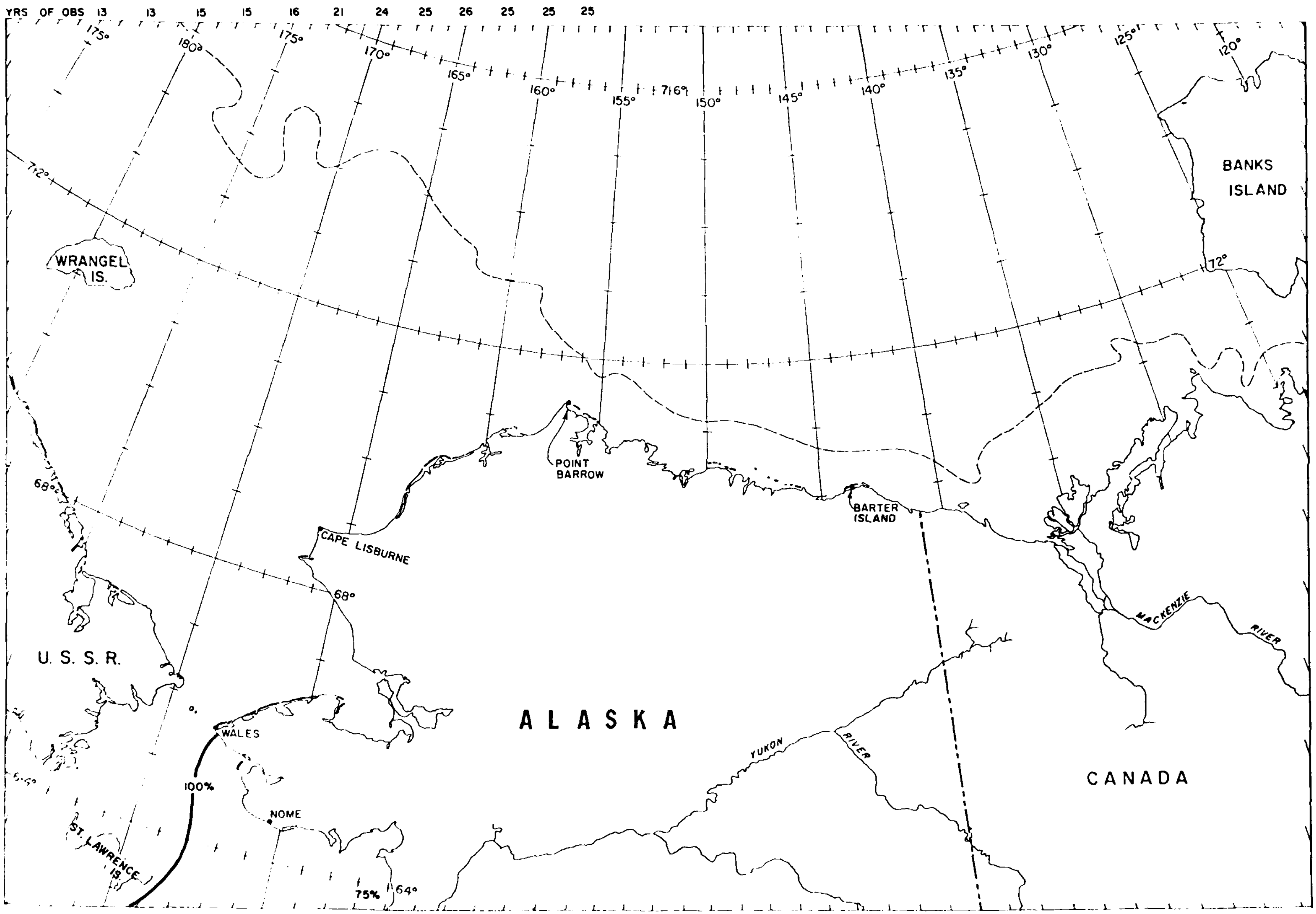

FIGURE 2 PROBABILITIES OF THE ICE LIMIT FOR MAY 15

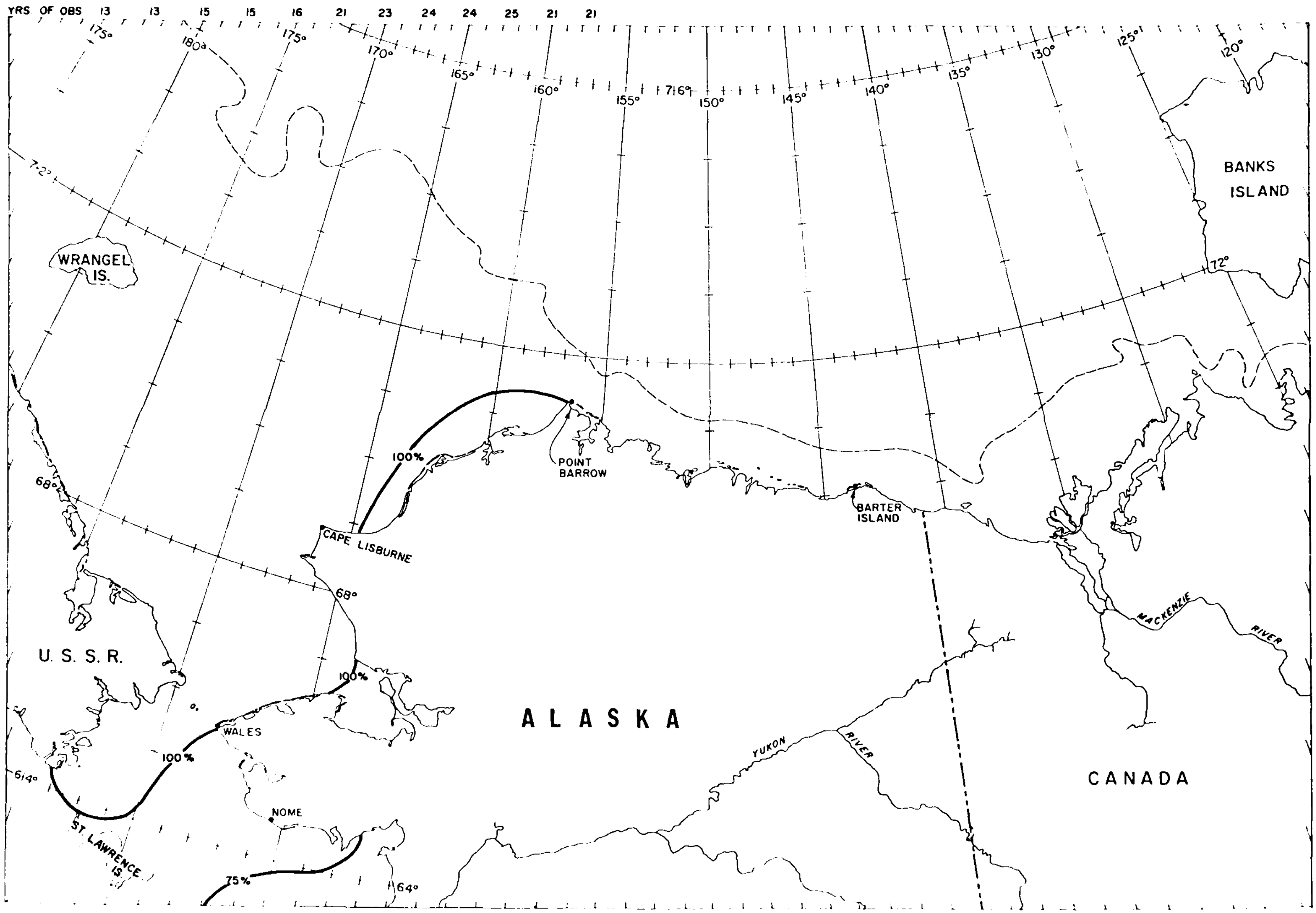

FIGURE 3. PROBABILITIES OF THE 50% ICE CONCENTRATION BOUNDARY FOR MAY 15

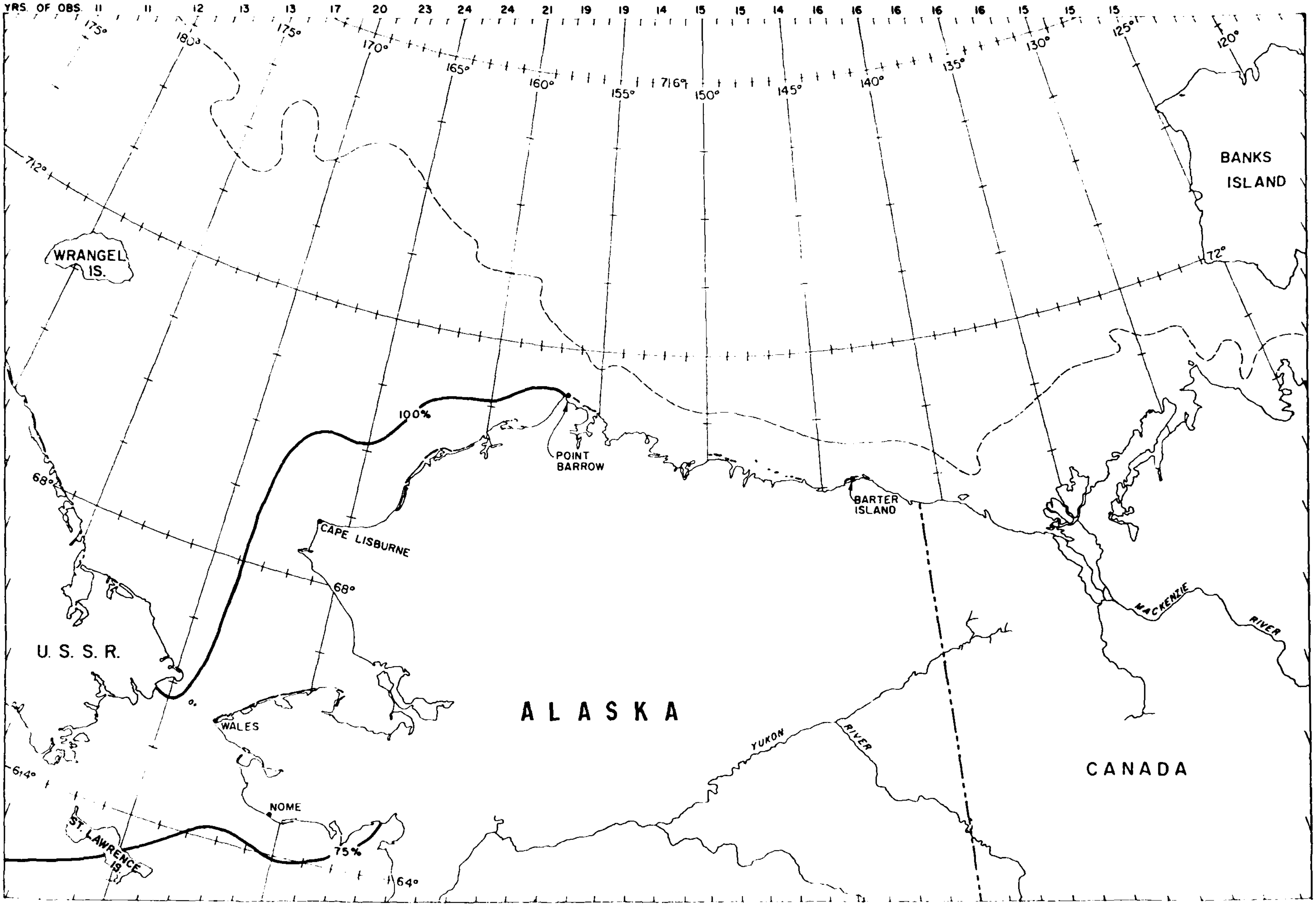

FIGURE 4 PROBABILITIES OF THE ICE LIMIT FOR JUNE 1

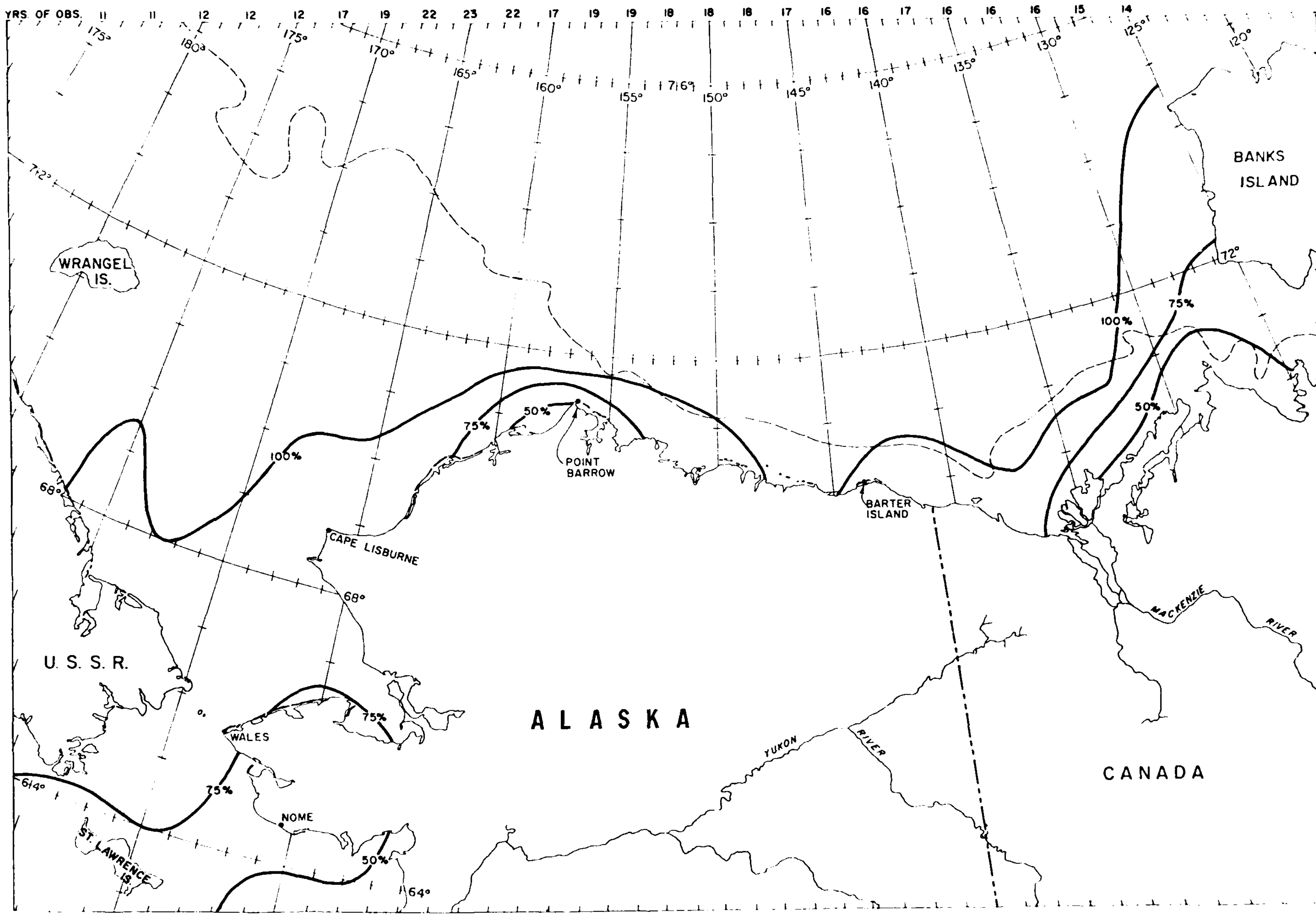

FIGURE 5. PROBABILITIES OF THE 50% ICE CONCENTRATION BOUNDARY FOR JUNE 1

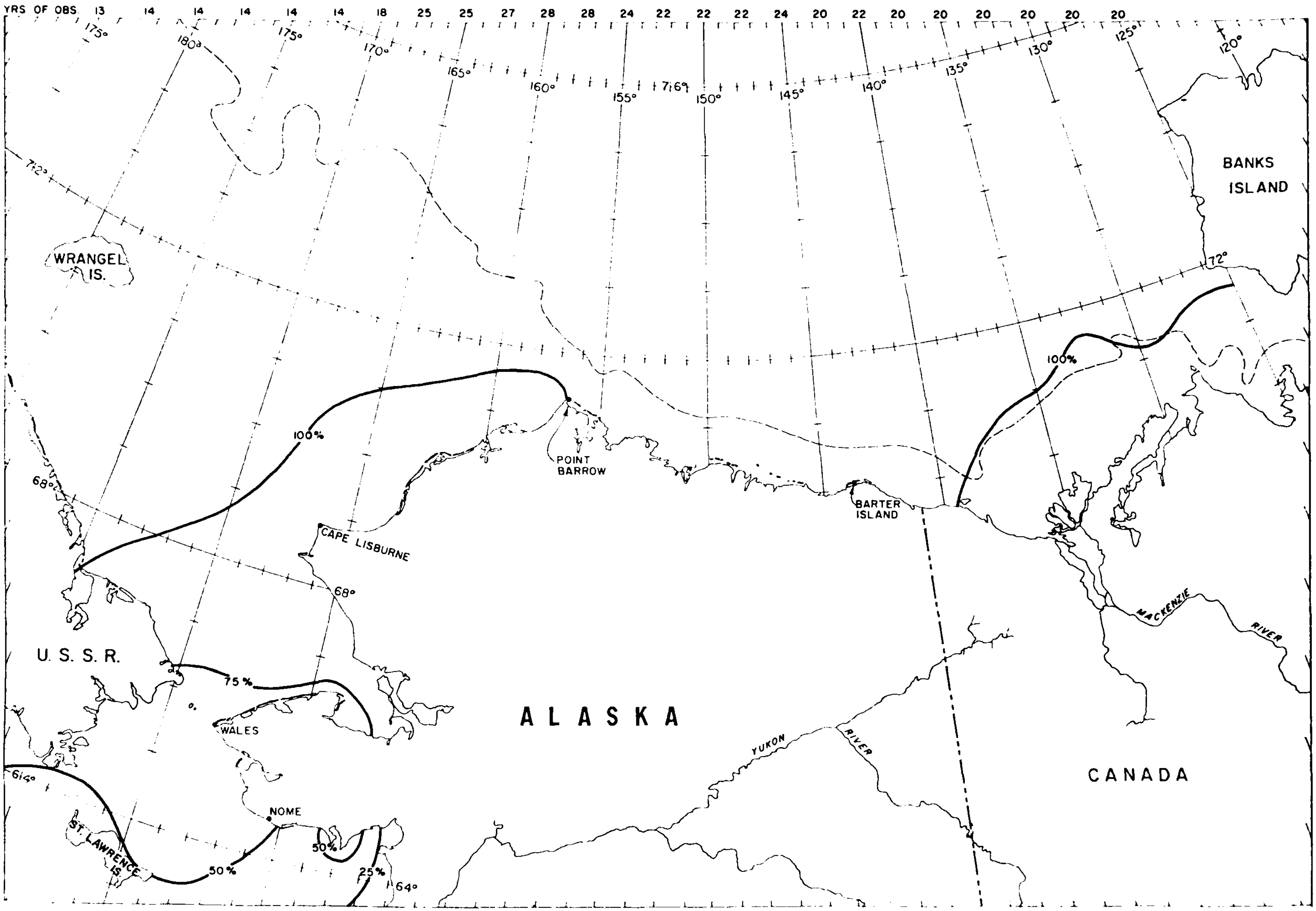

FIGURE 6. PROBABILITIES OF THE ICE LIMIT FOR JUNE 15

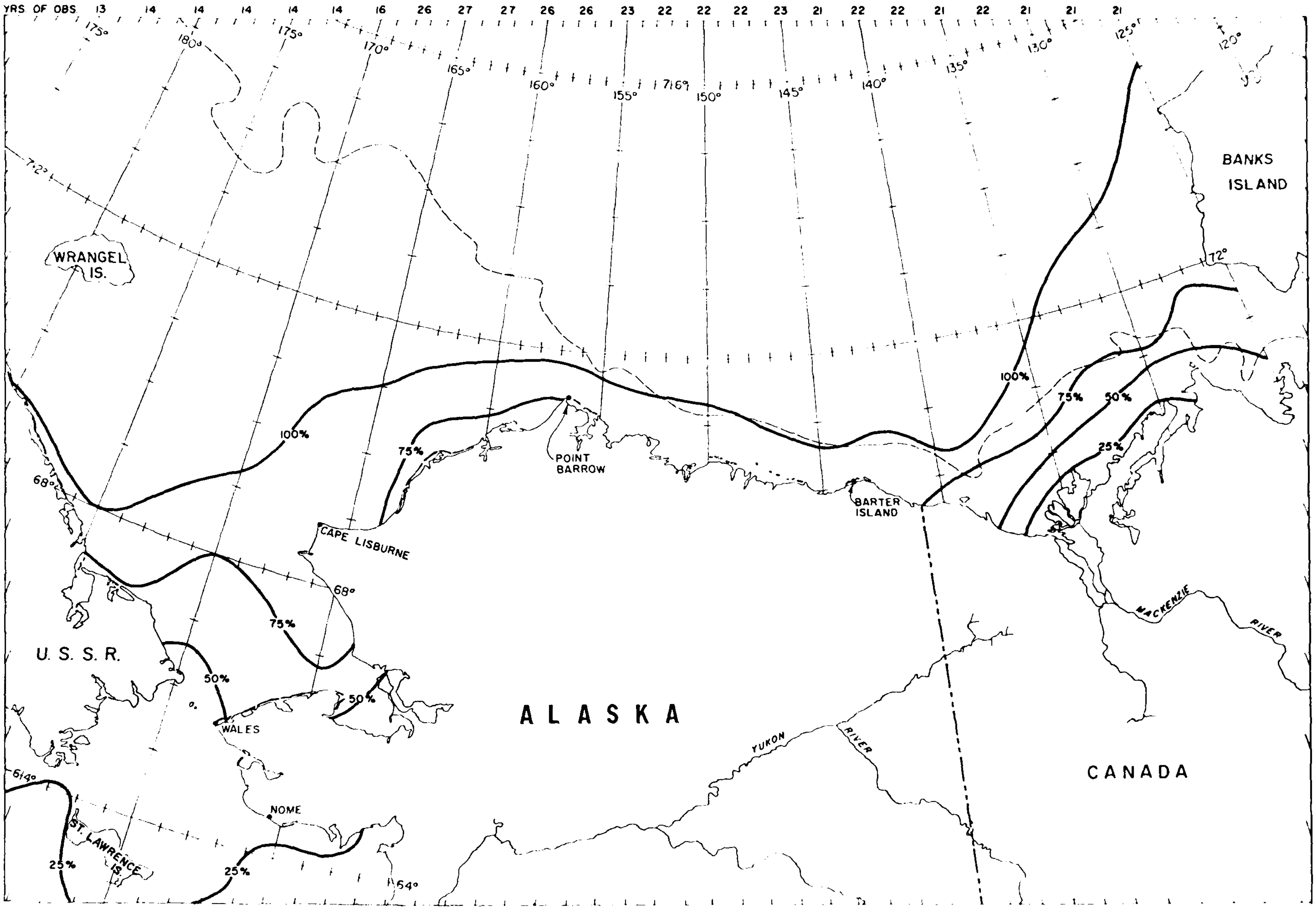

FIGURE 7 PROBABILITIES OF THE 50% ICE CONCENTRATION BOUNDARY FOR JUNE 15

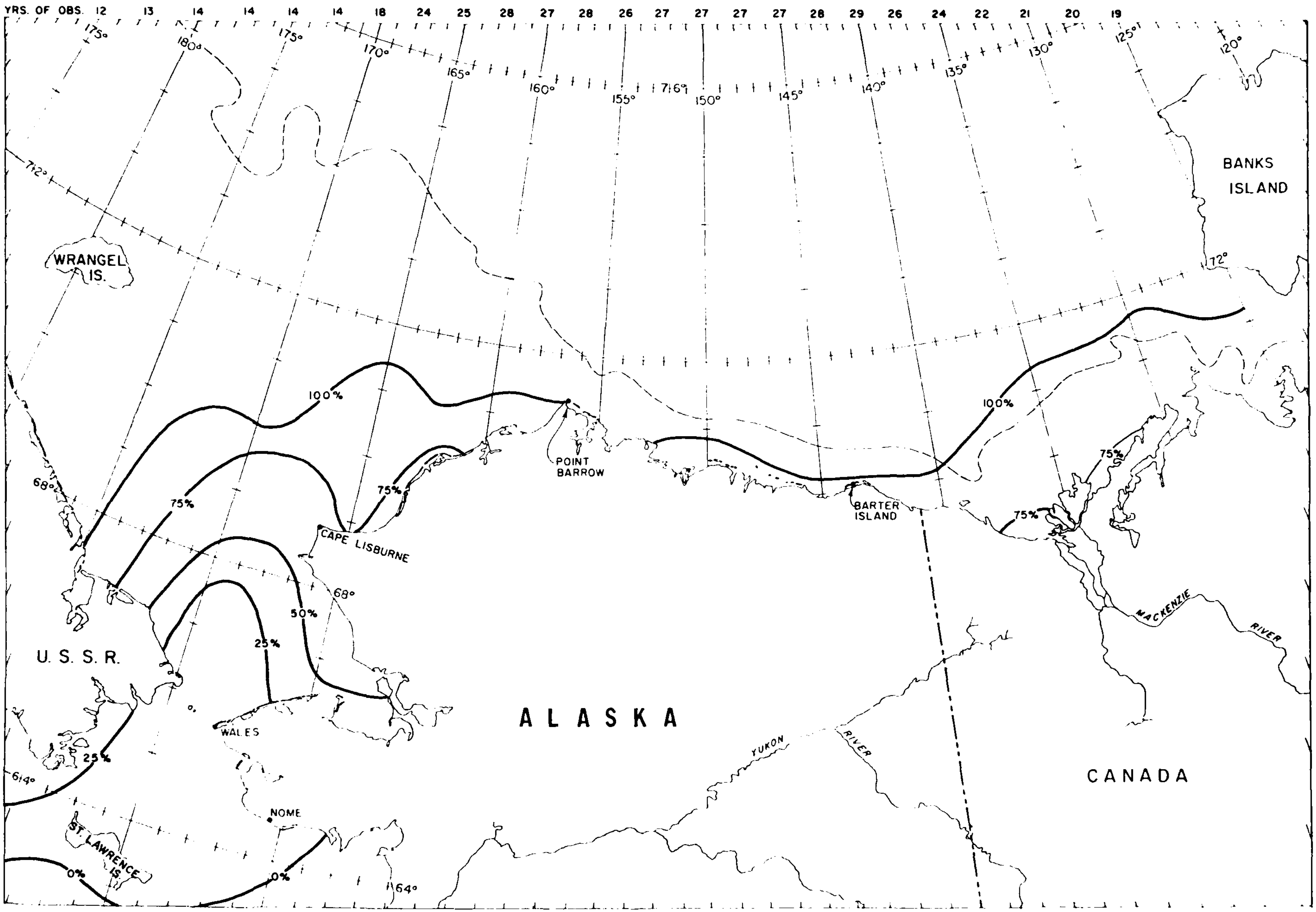

FIGURE 8. PROBABILITIES OF THE ICE LIMIT FOR JULY 1

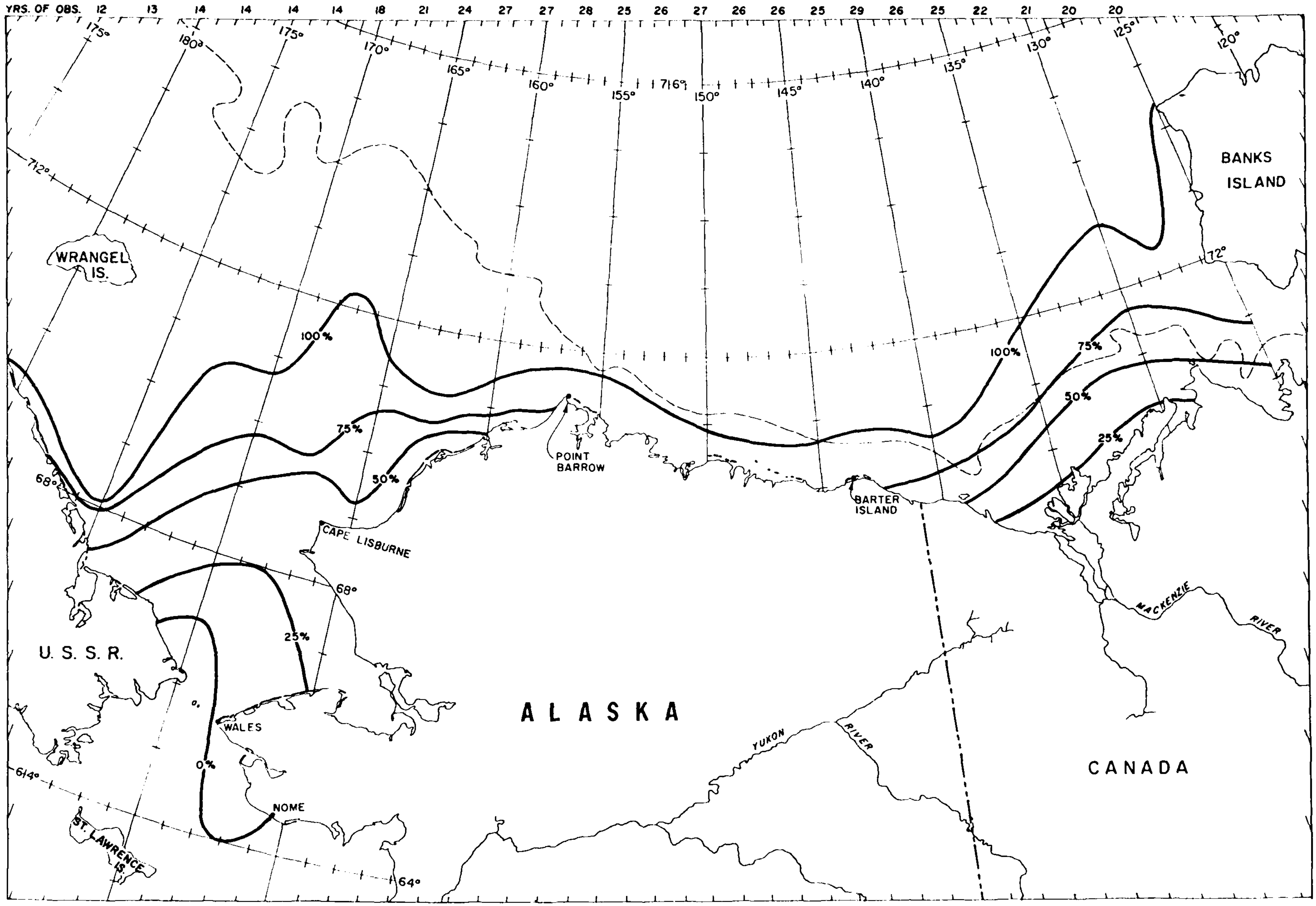

FIGURE 9. PROBABILITIES OF THE 50% ICE CONCENTRATION BOUNDARY FOR JULY 1

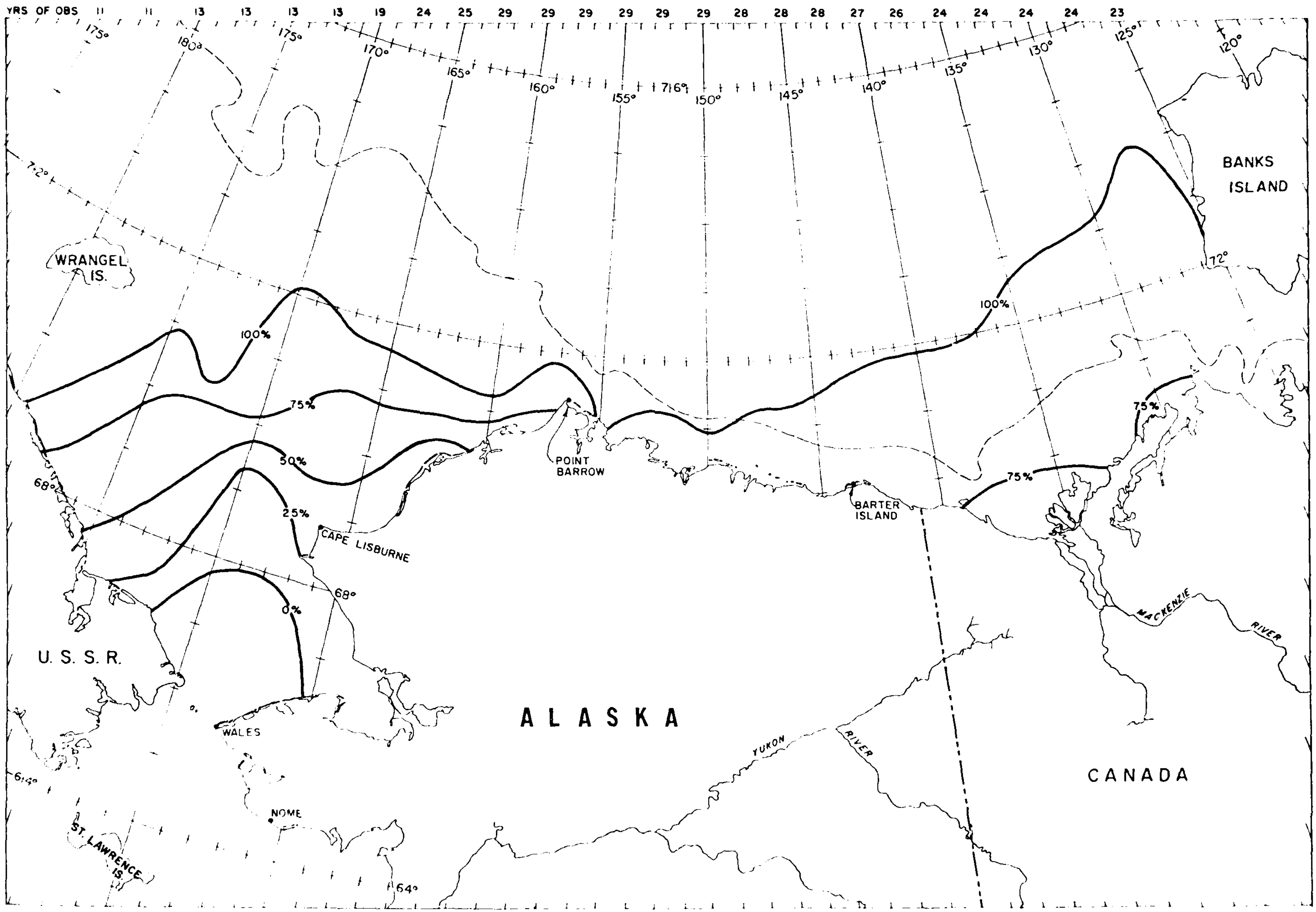

FIGURE 10. PROBABILITIES OF THE ICE LIMIT FOR JULY 15

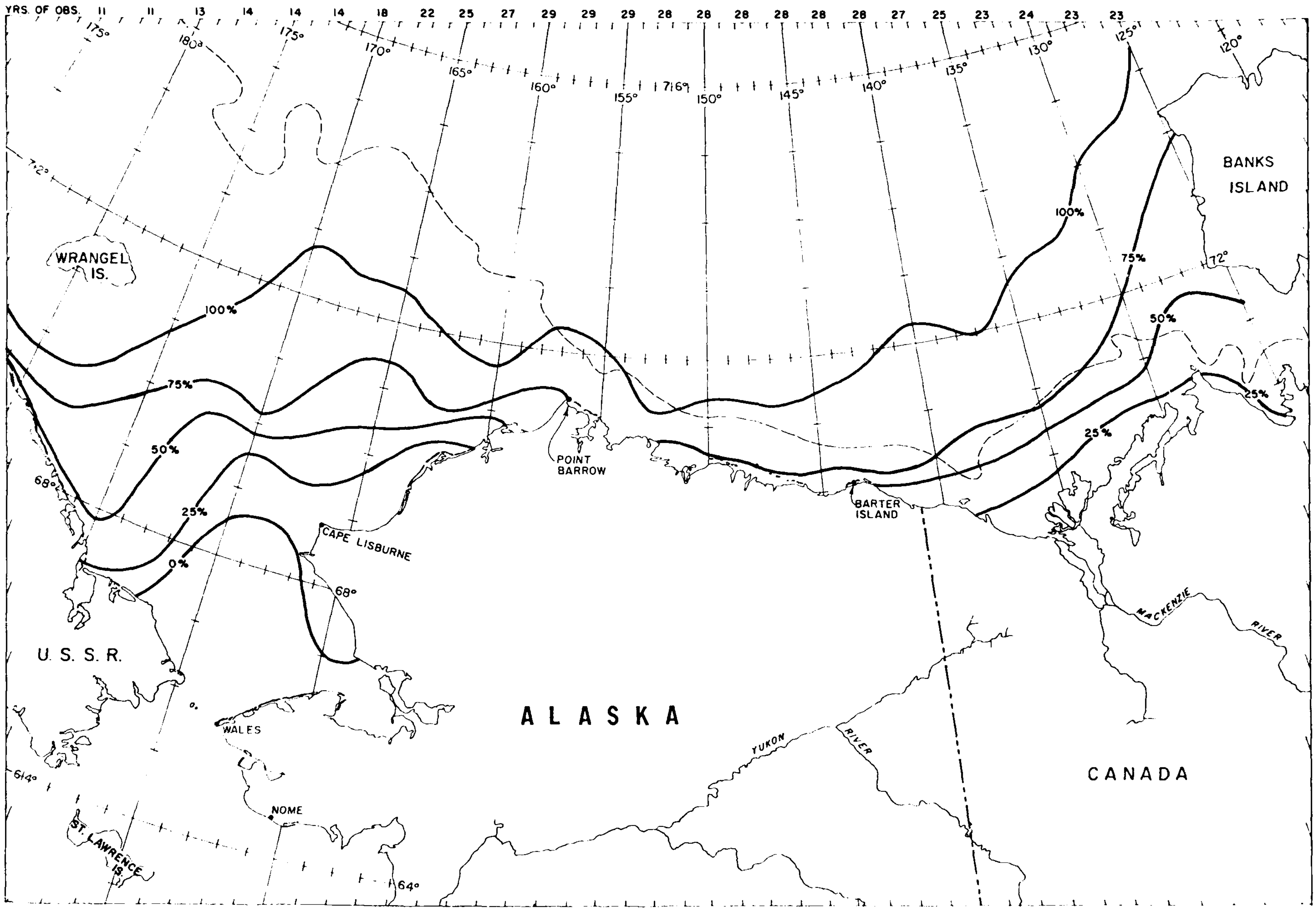

FIGURE 11. PROBABILITIES OF THE 50% ICE CONCENTRATION BOUNDARY FOR JULY 15

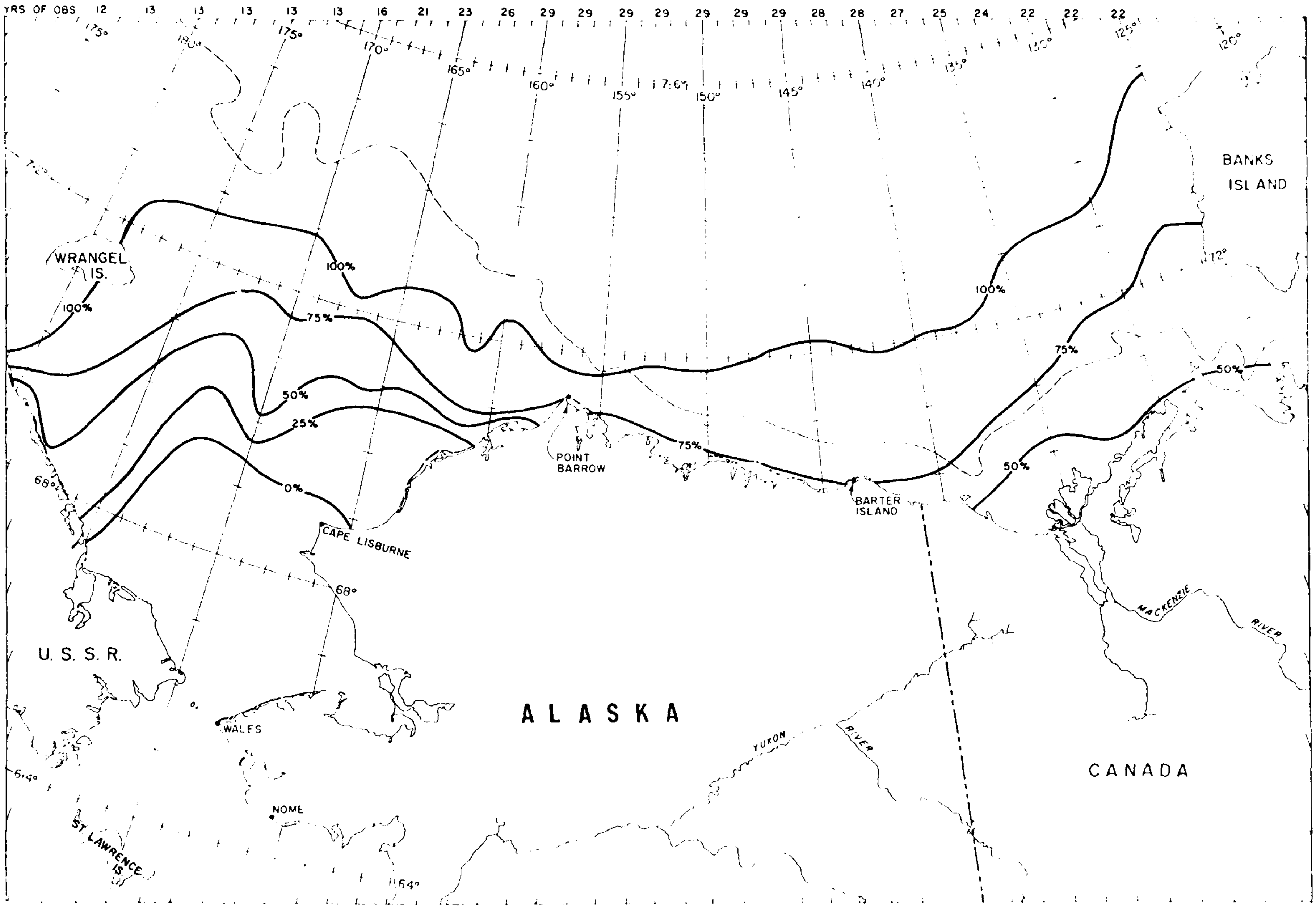

FIGURE 12. PROBABILITIES OF THE ICE LIMIT FOR AUGUST 1

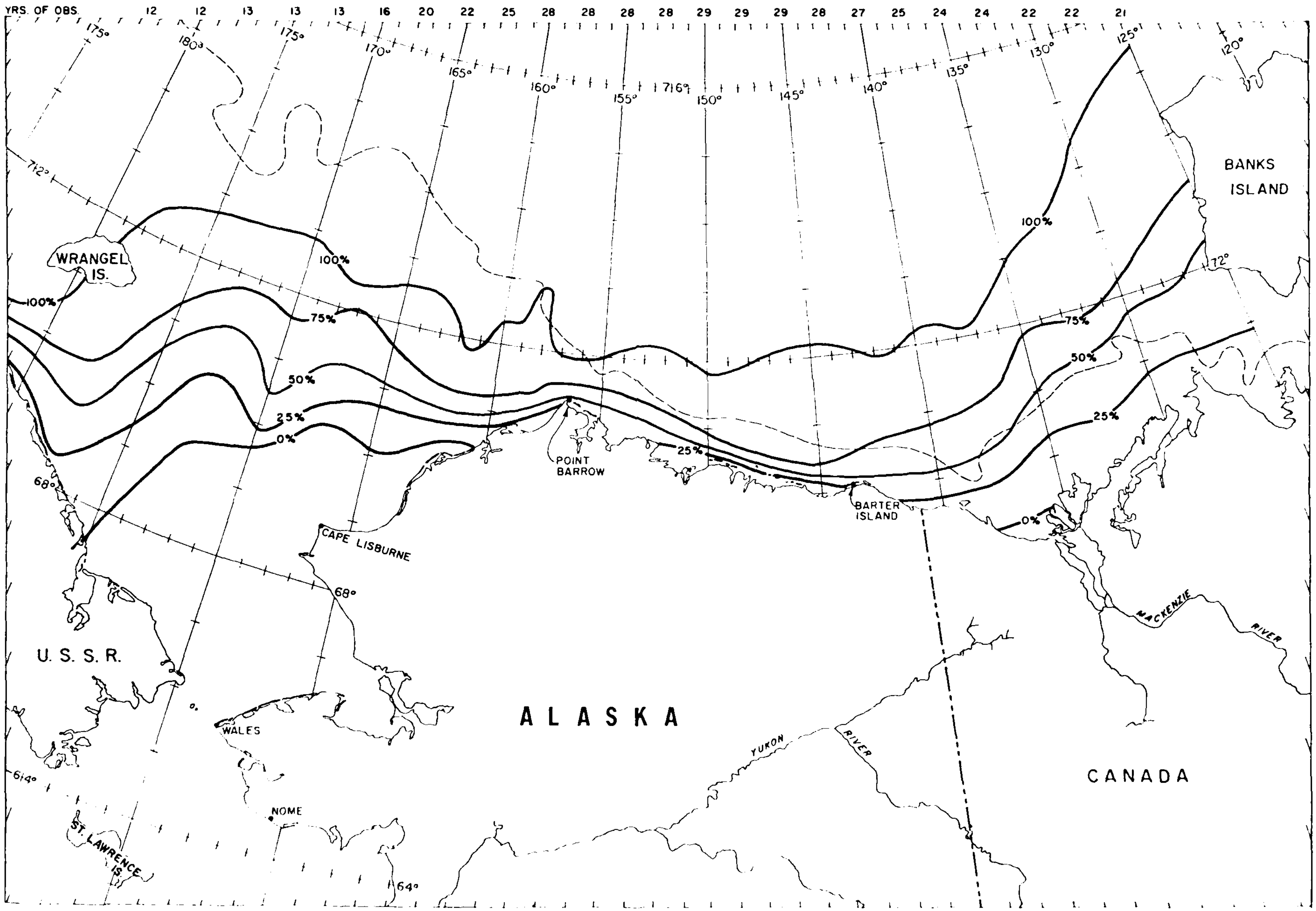

FIGURE 13. PROBABILITIES OF THE 50% ICE CONCENTRATION BOUNDARY FOR AUGUST 1

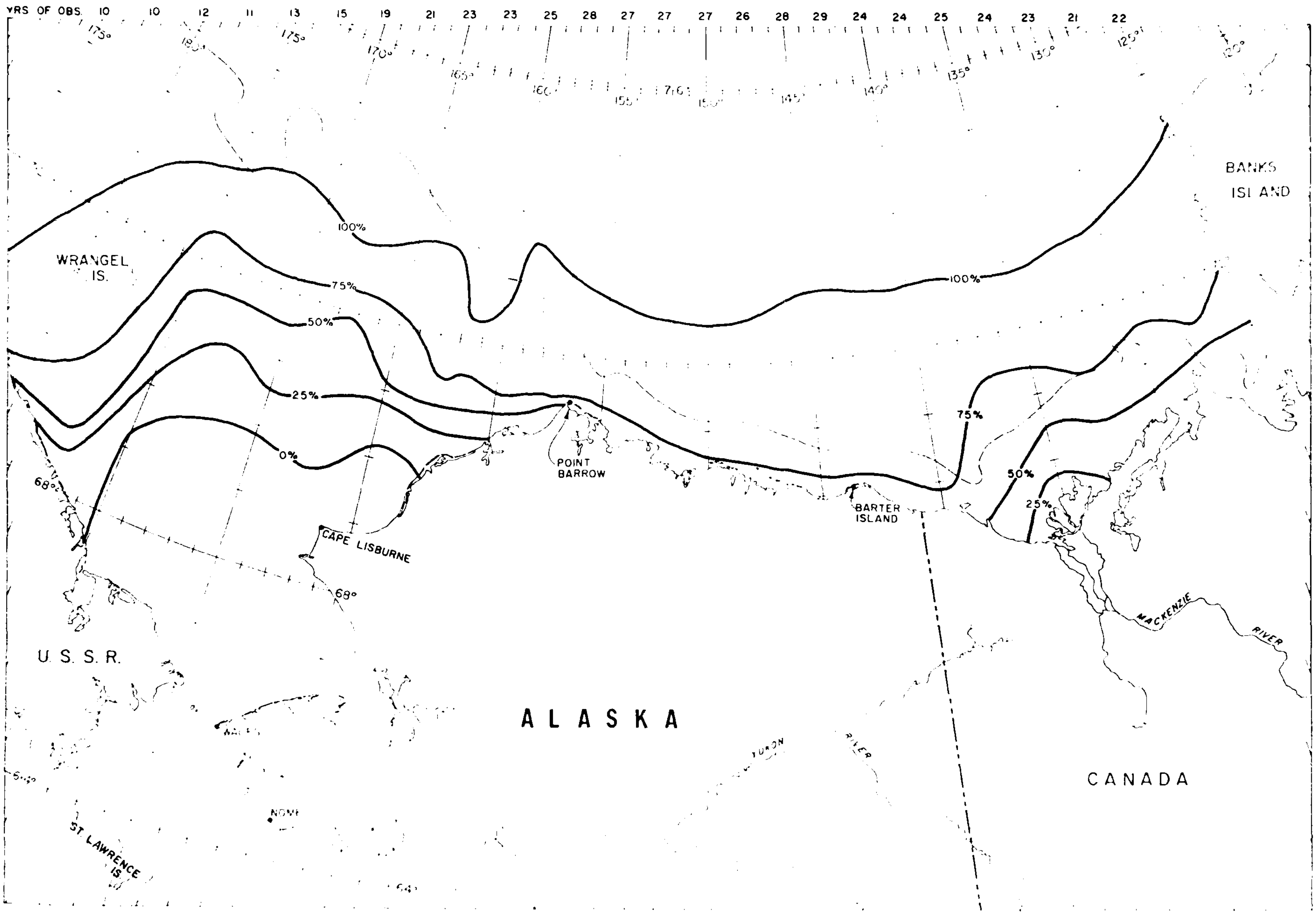

FIGURE 14 PROBABILITIES OF THE ICE LIMIT FOR AUGUST 15

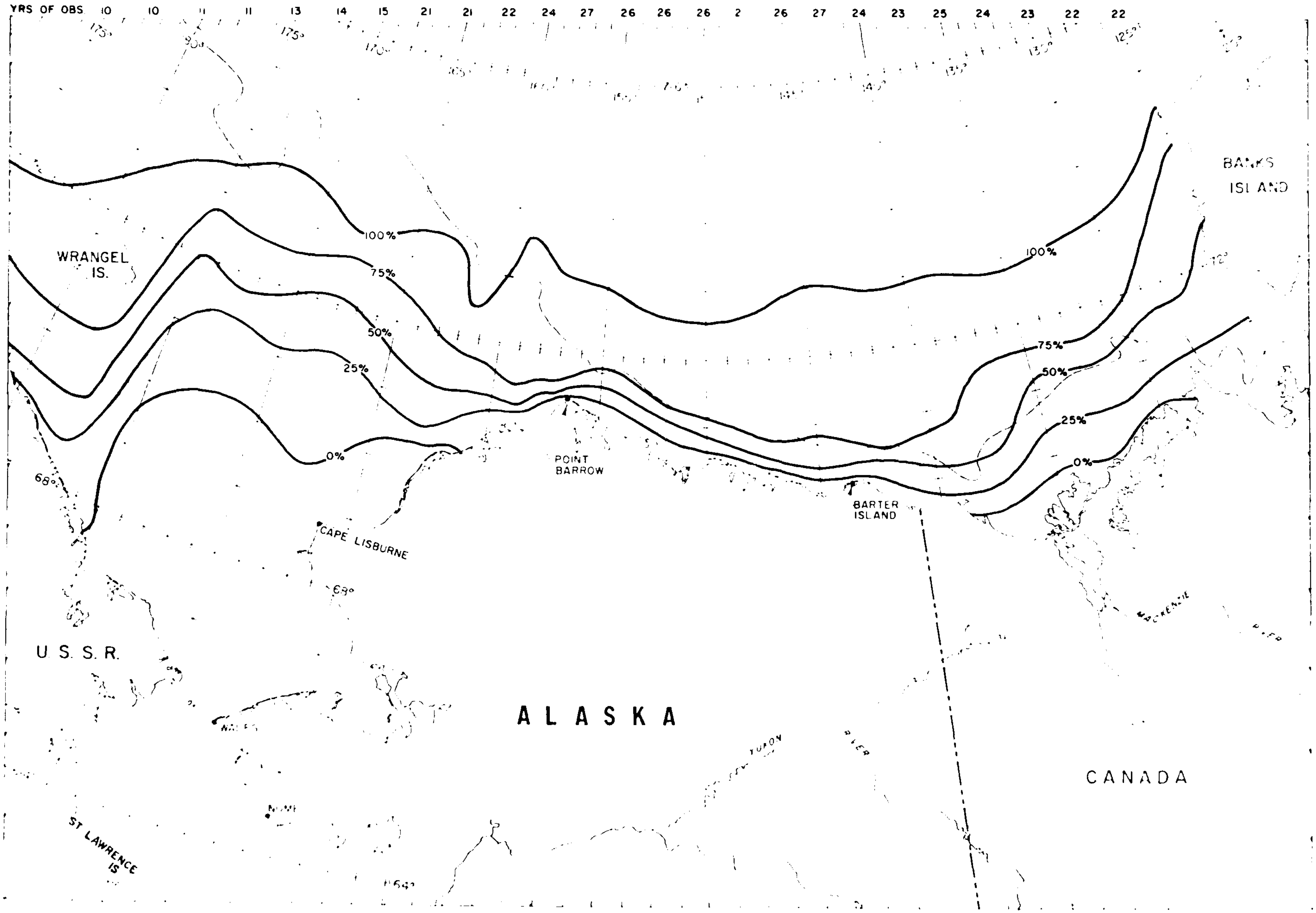

FIGURE 15. PROBABILITIES OF THE 50% ICE CONCENTRATION BOUNDARY FOR AUGUST 15

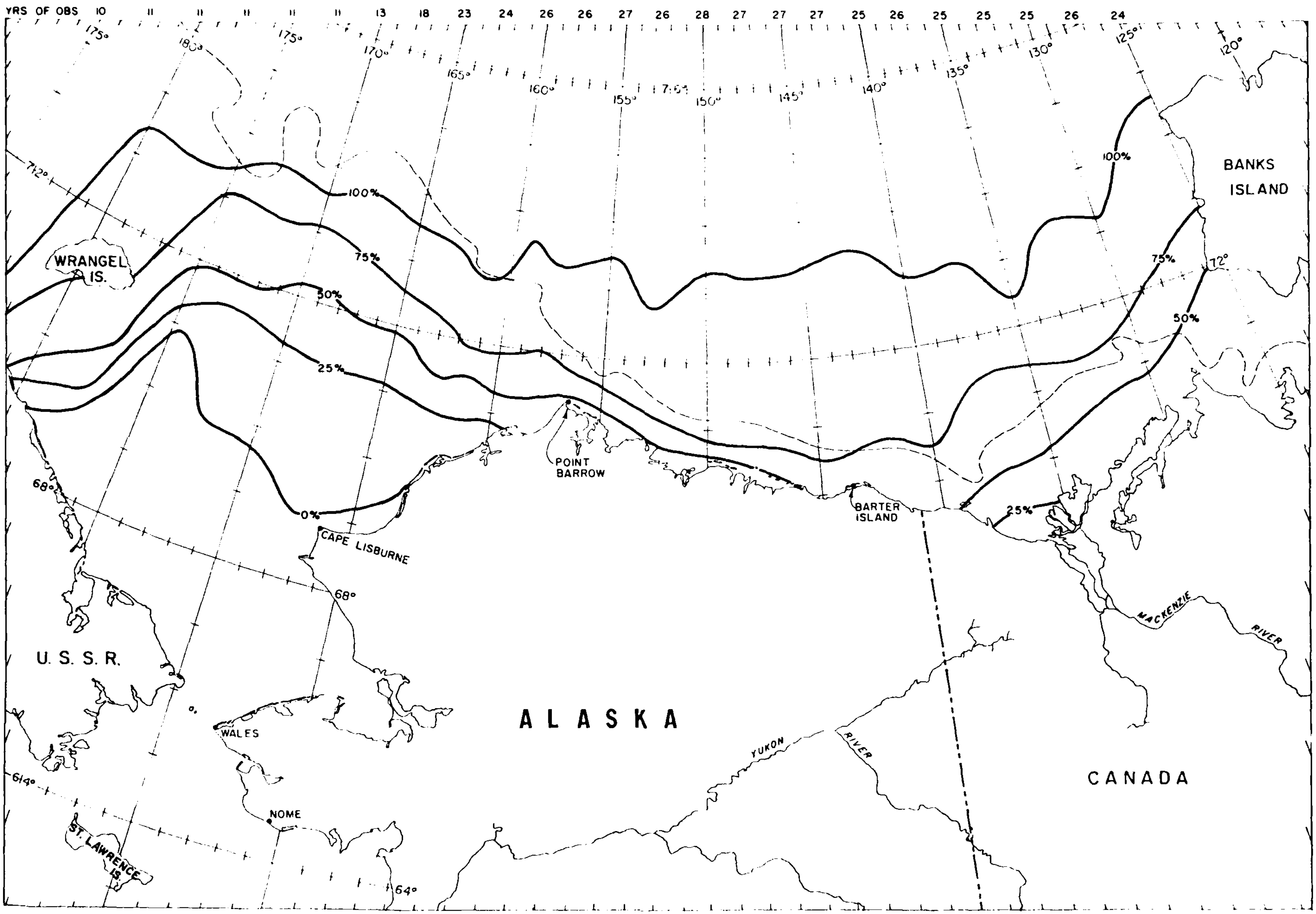

FIGURE 16 PROBABILITIES OF THE ICE LIMIT FOR SEPTEMBER 1

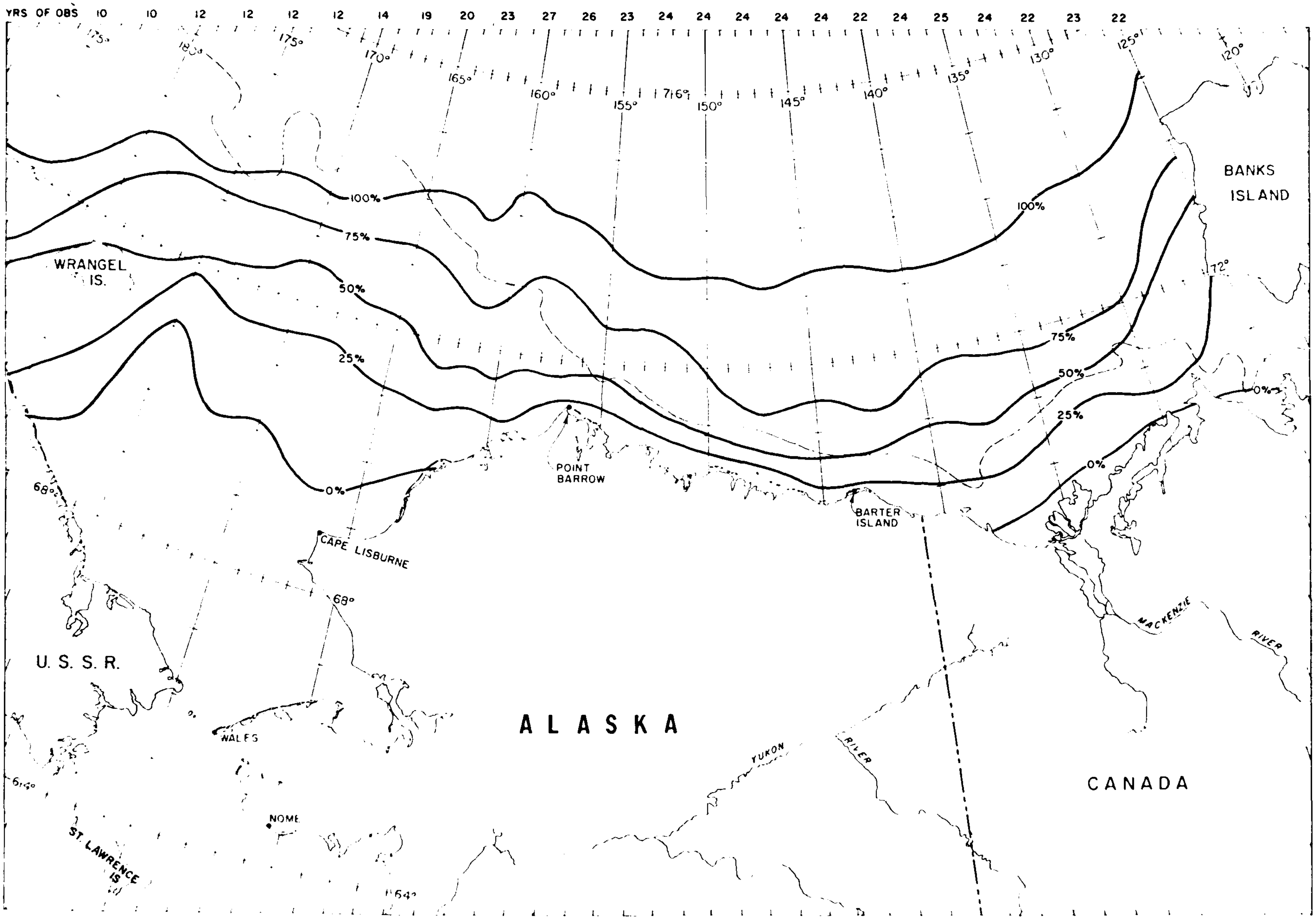

FIGURE 17 PROBABILITIES OF THE 50% ICE CONCENTRATION BOUNDARY FOR SEPTEMBER 1

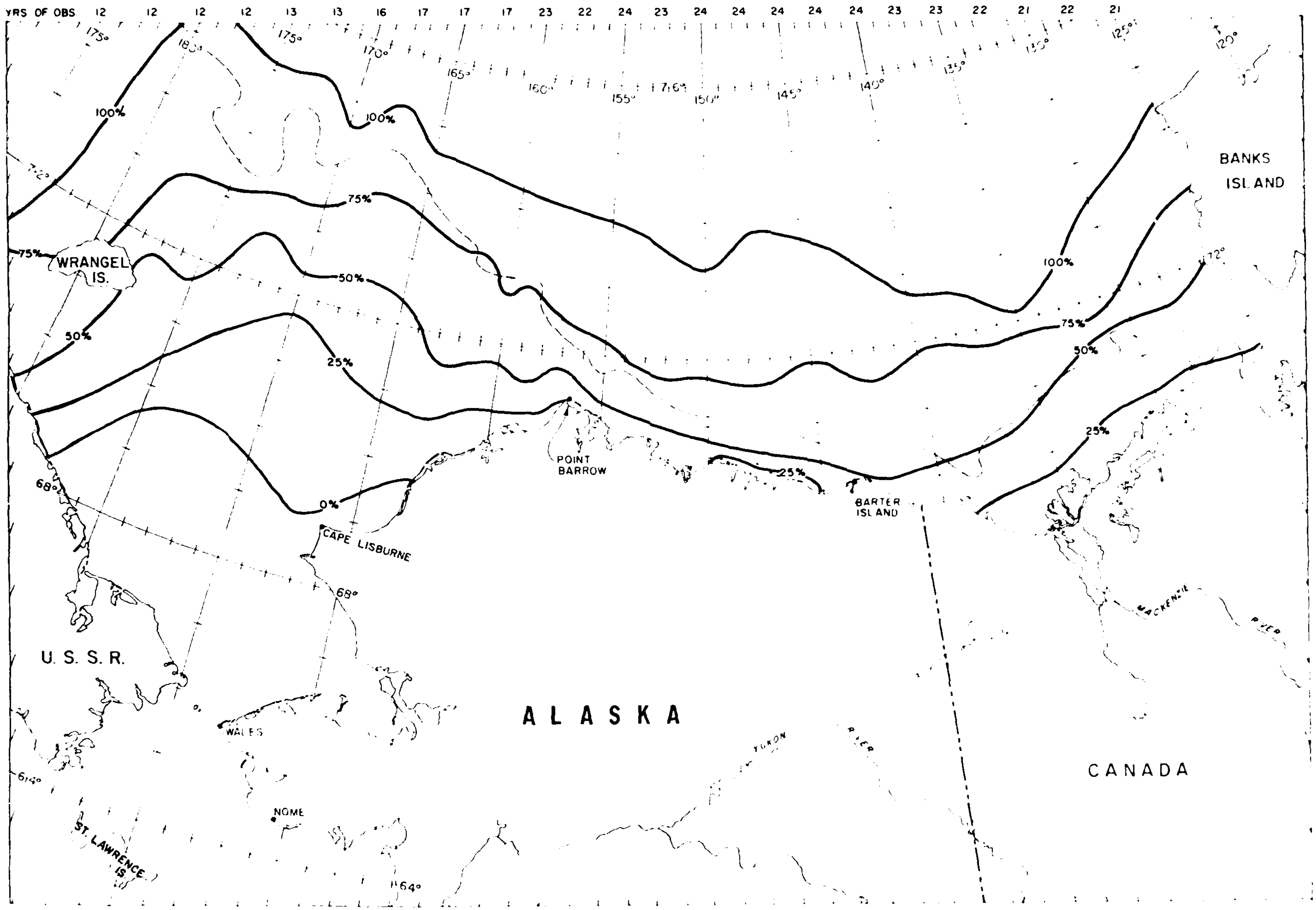

FIGURE 18 PROBABILITIES OF THE ICE LIMIT FOR SEPTEMBER 15

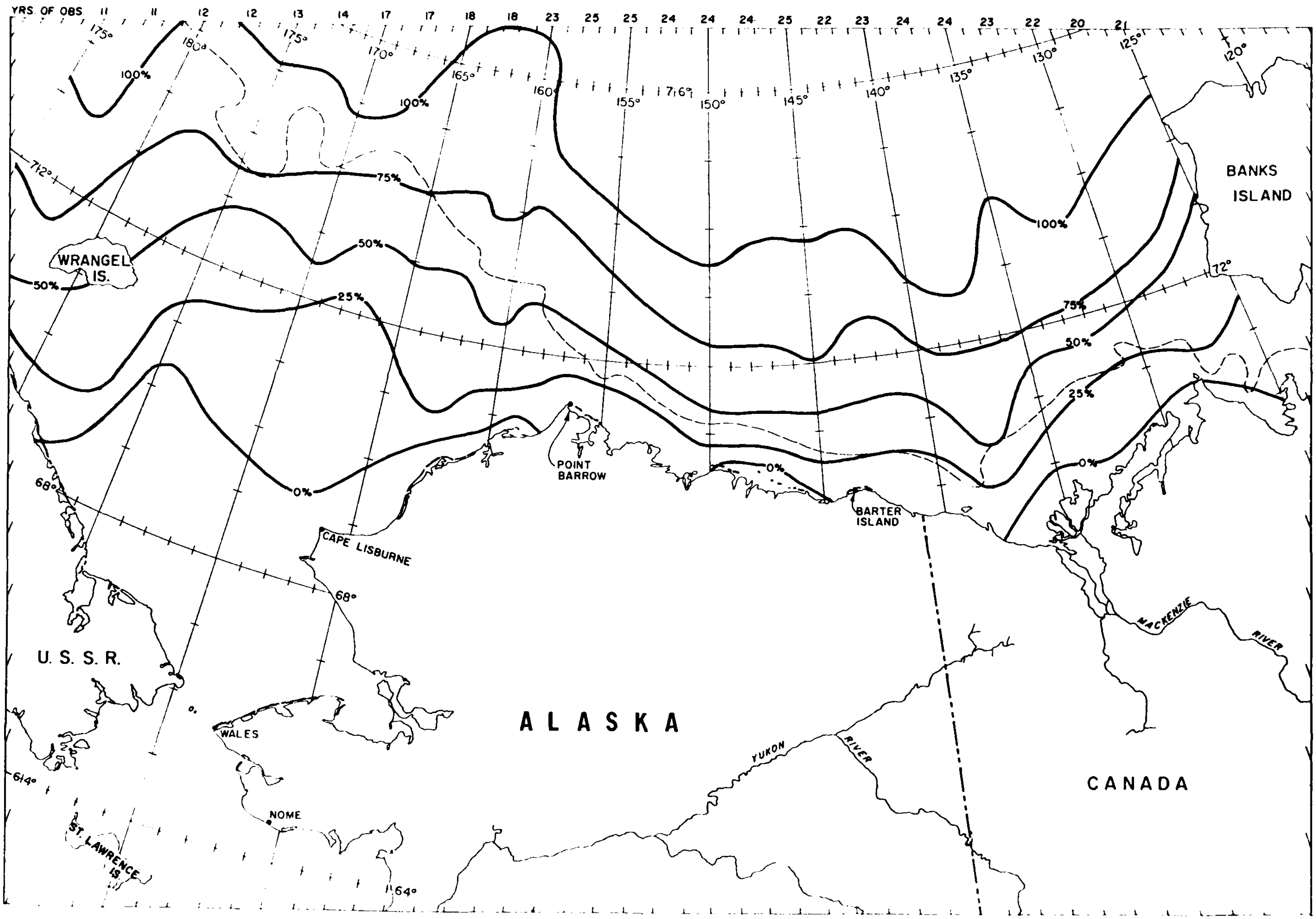

FIGURE 19 PROBABILITIES OF THE 50% ICE CONCENTRATION BOUNDARY FOR SEPTEMBER 15

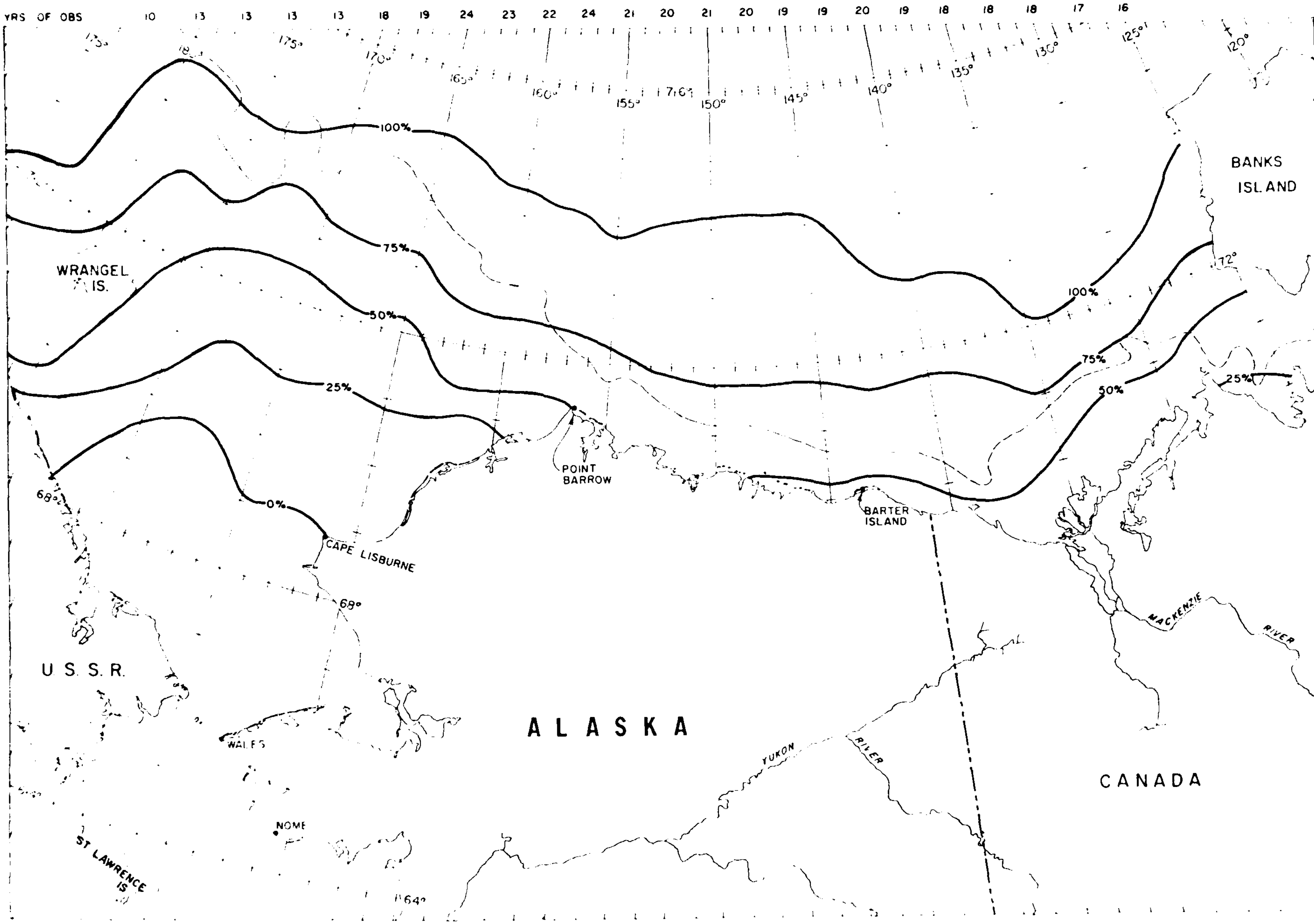

FIGURE 20 PROBABILITIES OF THE ICE LIMIT FOR OCTOBER 1

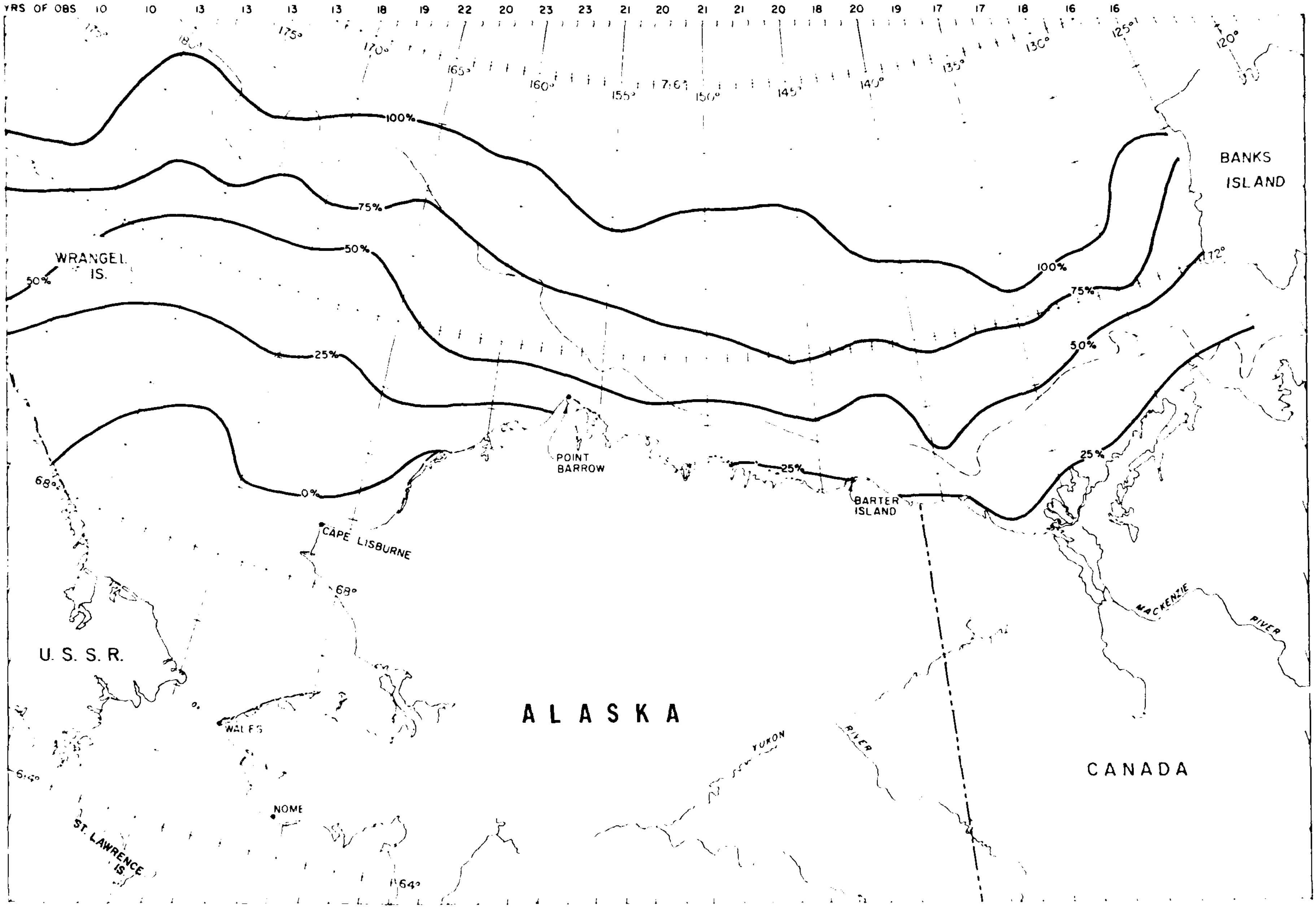

FIGURE 21 PROBABILITIES OF THE 50% ICE CONCENTRATION BOUNDARY FOR OCTOBER 1

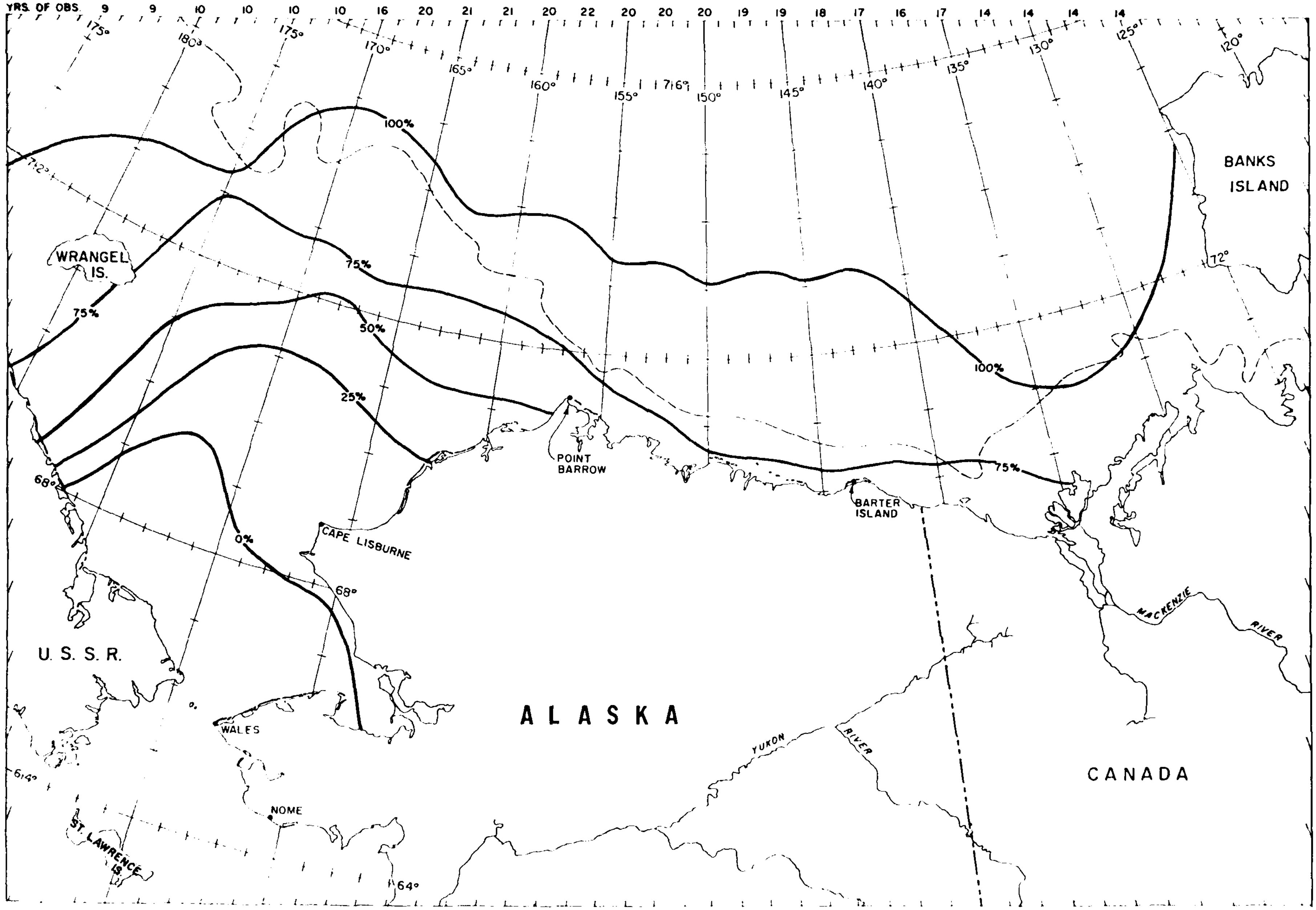

FIGURE 22 PROBABILITIES OF THE ICE LIMIT FOR OCTOBER 15

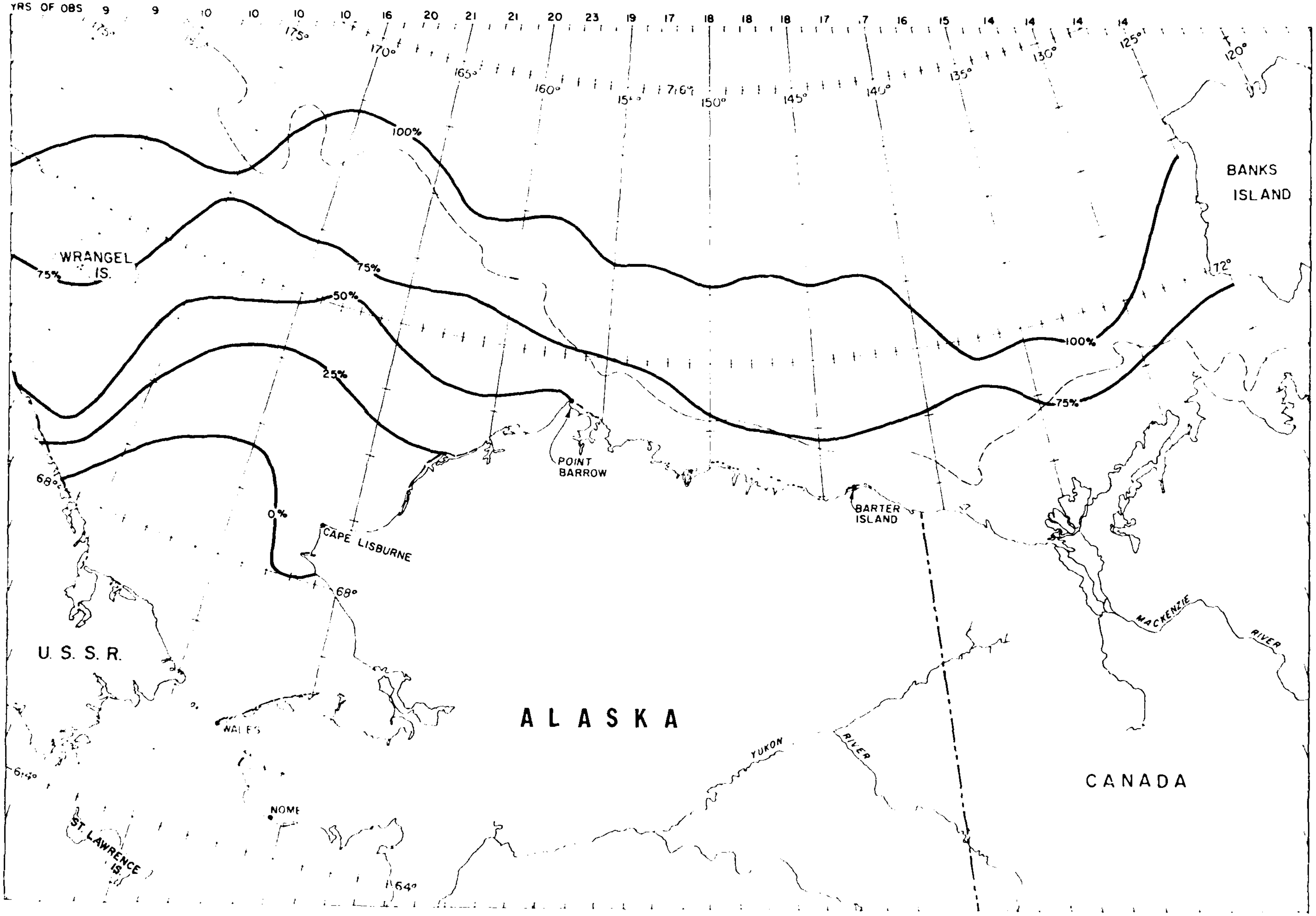

FIGURE 23. PROBABILITIES OF THE 50% ICE CONCENTRATION BOUNDARY FOR OCTOBER 15

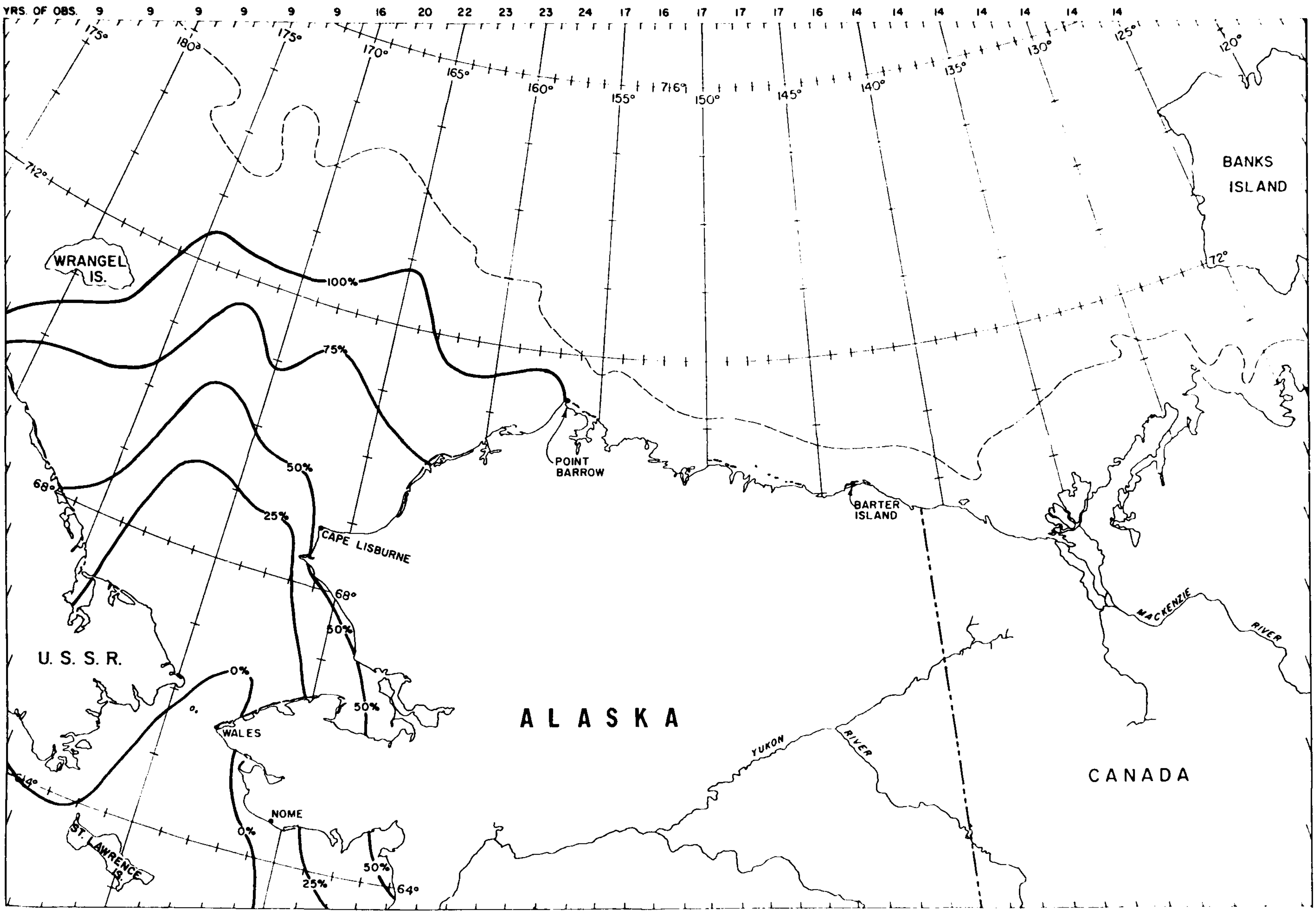

FIGURE 24. PROBABILITIES OF THE ICE LIMIT FOR NOVEMBER 1

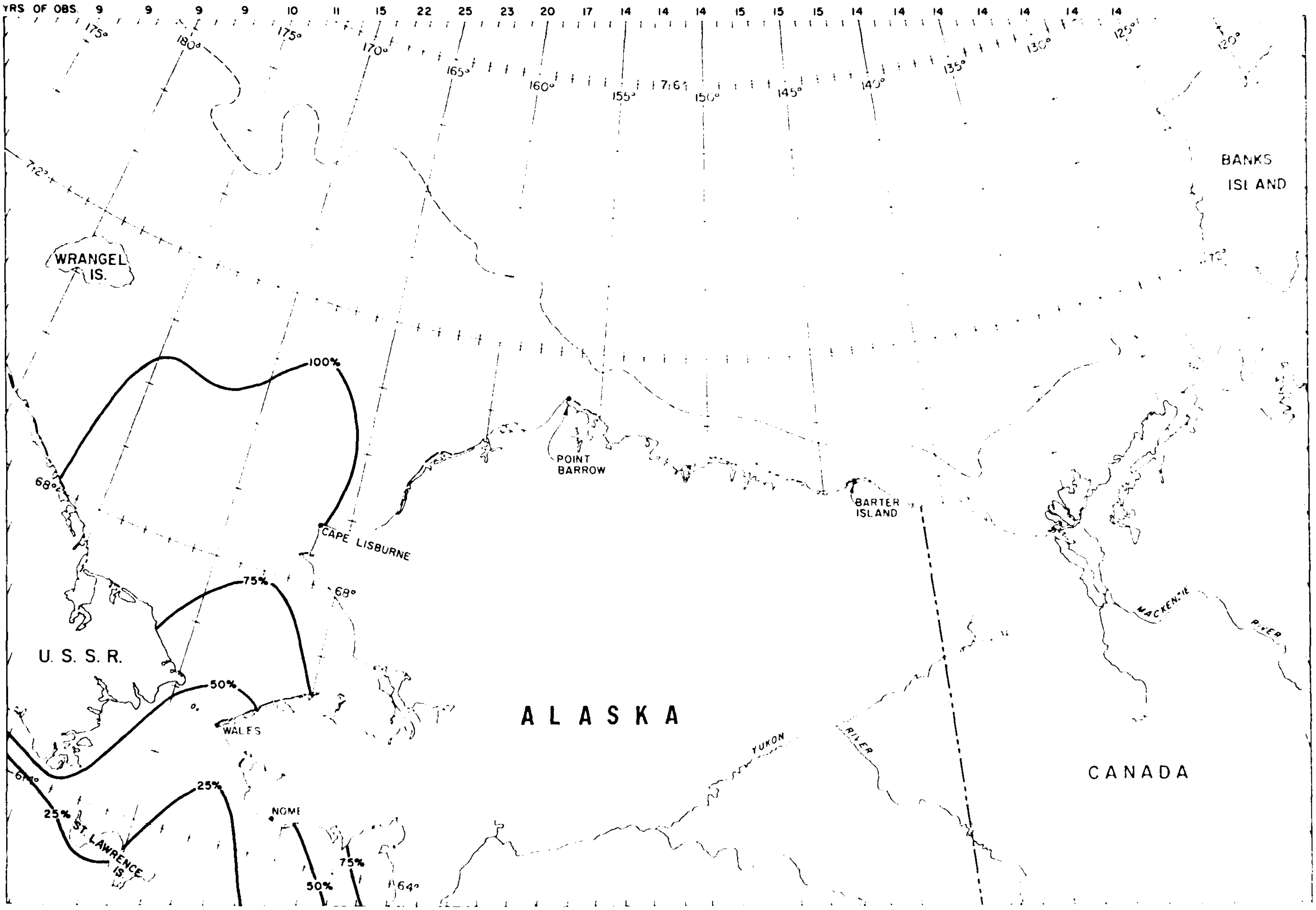

FIGURE 25. PROBABILITIES OF THE ICE LIMIT FOR NOVEMBER 15

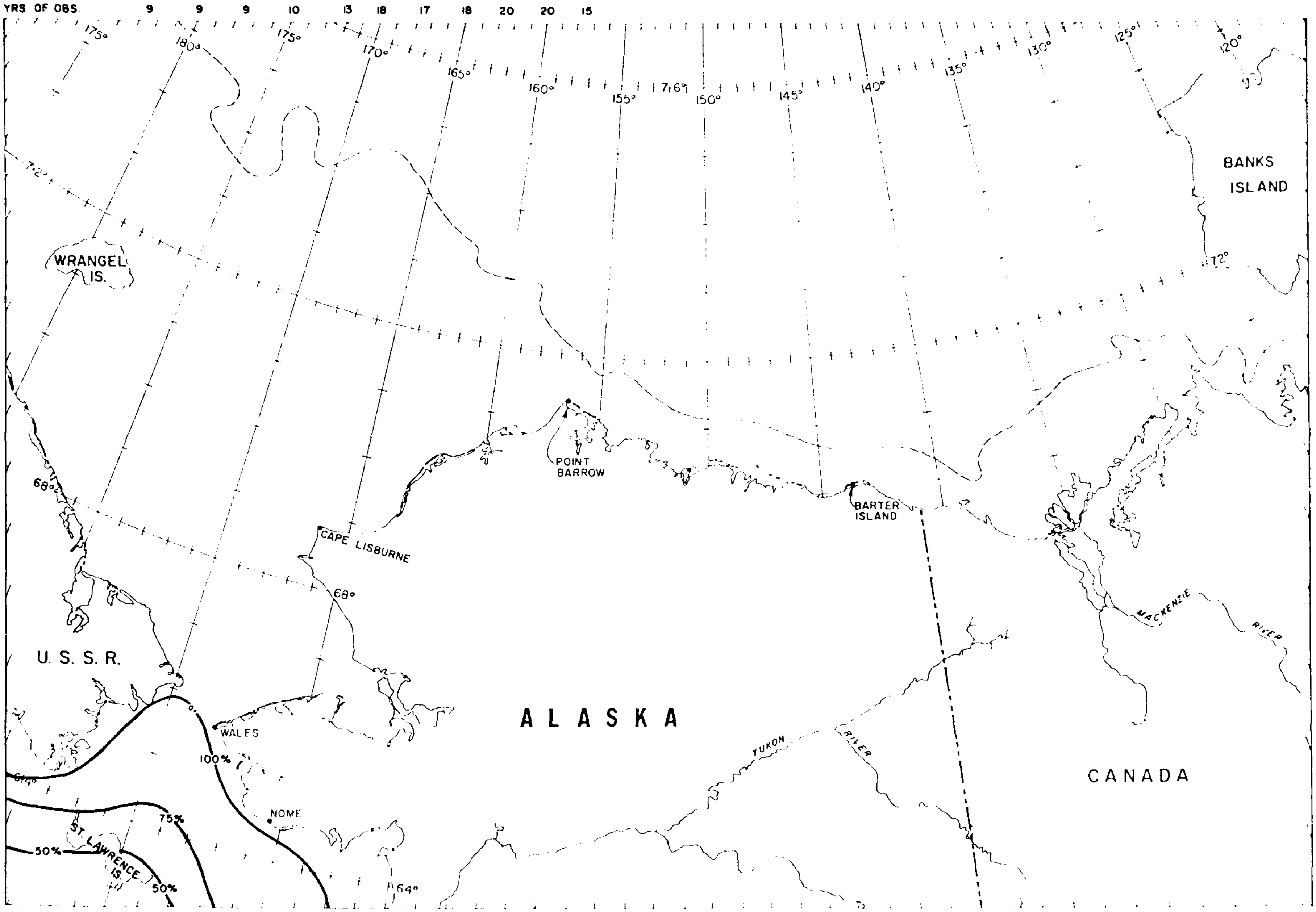

FIGURE 26 PROBABILITIES OF THE ICE LIMIT FOR DECEMBER 1

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